Does somatosensory function relate to bimanual function in children with unilateral cerebral palsy?

Non Peer-reviewed author version

KLEEREN, Lize; Mailleux, Lisa; Campenhout, Anja Van; Lambercy, Olivier; KLINGELS, Katrijn & Feys, Hilde (2026) Does somatosensory function relate to bimanual function in children with unilateral cerebral palsy?.

DOI: 10.21203/rs.3.rs-9201856/v1
Handle: http://hdl.handle.net/1942/49608

Does somatosensory function relate to bimanual function in children with unilateral cerebral palsy?

Lize Kleeren
lize.kleeren@kuleuven.be

KU Leuven, Hasselt University https://orcid.org/0000-0002-4649-4662

Lisa Mailleux
KU Leuven https://orcid.org/0000-0002-9955-098X

Anja Van Campenhout
University Hospitals Leuven, KU Leuven https://orcid.org/0000-0002-8158-5535

Olivier Lambercy
ETH Zurich, Signapore-ETH Centre https://orcid.org/0000-0002-0760-7054

Katrijn Klingels
Hasselt University, KU Leuven https://orcid.org/0000-0001-5853-9680

Hilde Feys
KU Leuven https://orcid.org/0009-0002-3858-3080

Research Article

Keywords: Upper limb, somatosensation, proprioception, bimanual function, unilateral cerebral palsy, children

Posted Date: March 25th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9201856/v1

Additional Declarations: The authors declare no competing interests.

Abstract

Background

Goal-directed bimanual movements rely on the integration of somatosensory information to plan and adjust motor actions. In children with unilateral cerebral palsy (uCP), previous studies have primarily relied on clinical assessments of bimanual function and proprioception, whereas robotic and instrumented assessments may provide more precise and objective measures to further outline this relationship.

Objectives

To investigate the association between tactile registration, tactile perception, proprioception and bimanual function in children with uCP, using both clinical and instrumented assessments.

Methods

In this cross-sectional study, sixty-one children with uCP (mean age 11y11mo (SD 3y0mo); 35 males) completed assessments of tactile registration, tactile perception and proprioception. Bimanual function was evaluated through functional hand use (Assisting Hand Assessment; Children's Hand-Use Experience Questionnaire), bimanual dexterity (Tyneside pegboard Test) and bimanual coordination (Ball-on-Bar task on the Kinarm robot; Box opening task). Associations were investigated using correlations (r/r_s) and multiple linear regressions (R^2).

Results

Worse tactile registration was weakly associated with reduced functional hand use (r_s=-0.320-(-0.408), $p \leq 0.032$). Worse tactile perception showed low to moderate associations with reduced functional hand use (r_s=-0.348-(-0.626), $p \leq 0.023$), slower bimanual dexterity (r_s=-0.478-(-0.574), $p < 0.001$) and poorer coordination ($|r_s|$=0.357–0.501, $p < 0.022$). Proprioceptive impairments were generally lowly to moderately related to functional hand use (r_s=-0.236-(-0.493), $p < 0.113$) and bimanual dexterity (r_s=0.279–0.509, $p < 0.095$). Regression analyses indicated that two-point discrimination, distal position sense and proximal position sense explained respectively 33–40% and 58% of the variance in functional hand use ($p < 0.050$) and of bimanual dexterity ($p < 0.050$). Variability in bimanual coordination was only minimally explained by proprioceptive measures (R^2=4%-9%, p = 0.024–0.081).

Conclusions

Higher-order tactile perception and proprioception are particularly relevant for functional hand use and bimanual dexterity in children with uCP, whereas associations with bimanual coordination are more task- and parameter dependent. The results emphasize the importance of integrating somatosensory assessments into the follow-up of children with uCP to further understand bimanual impairments.

1. INTRODUCTION

Goal-directed movements depend on the accurate integration of somatosensory input, which provides the feedback necessary to plan, guide and adjust motor actions [1, 2]. Integration of tactile and proprioceptive information relies on distributed neural networks [3]. Early brain lesions, such as those occurring in children with cerebral palsy (CP), can disrupt these networks, leading to somatosensory impairments and altered sensorimotor processing [4–6]. Unilateral cerebral palsy (uCP) is the most prevalent subtype, accounting for approximately 40% of the cases [7]. Although motor impairments are the most apparent symptom in children with uCP, somatosensory impairments are a well-established comorbidity [8–11].

Somatosensation refers to the ability to process and interpret bodily sensory information and encompasses tactile function and proprioception [12]. Tactile function further includes tactile registration, reflecting the initial awareness of a tactile stimulus and tactile perception, which additionally involves interpretation of the stimulus [13]. Proprioception, in turn, refers to the ability to accurately perceive limb positions and movements [14]. Previous studies have shown that somatosensory impairments across all modalities are common in children with uCP, with reported prevalence rates of up to 90% [8–11].

Somatosensory impairments may further compromise the execution of complex motor actions, particularly bimanual tasks requiring coordinated use of both hands. During the performance of bimanual activities, continuous integration of tactile and proprioceptive information is essential to synchronize the movements of both hands and ensure successful task performance [1]. For example, when opening a container, tactile feedback provides information about surface properties and lid position, needed to regulate grip forces and appropriately position the hands. Proprioceptive input from both hands additionally supports stabilization of the container as the other hand twists or pulls off the lid.

Two recent systematic reviews indeed reported a moderate to high association between tactile perception and bimanual function in children with CP [15, 16]. For tactile registration, however, evidence was limited with only five studies investigating this relation, of which three reported no to low associations [15]. Information regarding proprioception is also scarce, with only a few studies reporting conflicting associations ranging from no to moderate association [15–17]. As proprioceptive accuracy has shown to be site- and method-specific, variability in assessment approaches may partially explain these inconsistencies [18]. Moreover, quantifying proprioception remains challenging due to the limited precision of current clinical assessments [19]. Robot-assisted technological assessments may overcome these limitations and provide deeper insight into the relation between proprioception and bimanual function.

Moreover, bimanual function is often evaluated using self-reported questionnaires or functional hand use measures, such as the Assisting Hand Assessment (AHA). While these tools are clinically relevant and widely used, they may not capture the precise temporal and spatial coordination between both hands [20, 21]. In contrast, technological assessments can provide detailed insight into complex bimanual motor tasks, including bimanual dexterity or the ability to perform fast and accurate movements and bimanual coordination or the ability to synchronize the upper limbs for a common goal [22–24]. Innovative tools such as three-dimensional motion analysis and robotics have been proposed to assess these aspects [25, 26]. Nevertheless, to the best of our knowledge, such fine-grained bimanual assessments have not yet been used to further delineate their potential relation with somatosensation in children with uCP.

Therefore, the main aims of this study were to: (1) map the relation between tactile registration, tactile perception, proprioception and different aspects of bimanual function, using a comprehensive test-battery encompassing functional hand use, bimanual dexterity and bimanual coordination; and (2) explore the extent to which somatosensory function explains variability across these different aspects of bimanual function. We additionally examined the association between measures of functional hand use and instrumented measures of bimanual dexterity and bimanual coordination to provide insight into the relationship between the different aspects of bimanual function. We hypothesized to find low to moderate correlations between tactile perception and proprioception and bimanual function, with stronger correlations expected for functional hand use and bimanual dexterity. We further expected that tactile perception and distal position sense would account for part of the variability in functional hand use, bimanual dexterity and bimanual coordination as measured with the box opening task, while variability in bimanual coordination measured with the Kinarm exoskeleton would be more determined by proximal position sense.

2. MATERIAL AND METHODS

2.1. Participants

Children with spastic uCP were recruited through the Cerebral Palsy Reference Center at the University Hospitals Leuven (Belgium). Eligible participants were between 7 and 15 years old, able to understand the assessment instructions and could actively grasp and hold an object with the more-impaired hand (House Functional Classification System ≥ 4) [27]. Children were excluded if they had received upper limb botulinum neurotoxin-A injection within the previous six months or had undergone upper limb surgery within the two previous years.

Ethical approval was granted by the Ethics Committee Research UZ/KU Leuven (S62906 and S67467). Written informed consent was obtained from the parents before participation. Children aged 12 years or older provided additional assent to participate.

2.2. Assessments

2.2.1. Somatosensory function

Somatosensory assessments were performed for the more-impaired upper limb only and comprised clinical measures of tactile registration and tactile perception as well as clinical and robotic measures of proprioception. Further details regarding the somatosensory assessments can be found elsewhere [11].

Tactile registration was assessed on the ventral surface of the index fingertip using the 20-item *Semmes-Weinstein monofilaments* (Jamar® Monofilaments, Bolingbrook, IL) [28, 29]. The assessment began with the filament representing the upper boundary of intact tactile registration (0.07 grams). Next, the difficulty was adapted based on the participant's response. The outcome corresponded to the thinnest filament that was correctly detected across three consecutive touches and was categorized as “intact” (0.008–0.07 grams), “impaired” (0.16–300 grams) and “absent” (if touches with the largest monofilament could not be perceived (> 300 grams)).

Tactile perception comprised stereognosis and two-point discrimination [30]. During the assessment of *stereognosis*, participants were asked to identify six out of 12 familiar objects, including three paired objects of similar size and shape (i.e., pen/pencil, coin/button, paperclip/safety pin) and three distinct items (e.g., marble, spoon, comb, ball, clothespin, key). The total number of correctly identified objects was recorded and further classified as “intact” (6 objects identified), “impaired” (4–5 objects) or “absent” (≤ 3 objects). *Two-point discrimination* was assessed on the ventral side of the index fingertip using an aesthesiometer (Lafayette Instrument, IN). Testing began at four millimeters and was adjusted according to the child's performance. The minimal distance recognized as two separate points across five consecutive trials was determined and classified as “intact” (2–4 mm), “impaired” (5–10 mm) or “absent” (> 10 mm).

Proprioception was assessed *clinically* by testing *movement sense* of the index finger [30]. Participants were asked to indicate when they perceived small-amplitude movements; if these were not detected, larger movements were performed. Movement sense was classified as “intact” when three small-amplitude movements were correctly perceived, “impaired” when only larger movements were detected and “absent” when no movements were perceived.

Next, previously validated robot-assisted assessments were used to further quantify proprioception. Participants performed a contralateral position matching task on the Kinarm exoskeleton robot (BKIN Technologies Ltd, Kingston, Canada) to evaluate position sense of the shoulder and elbow joints, which will be referred to as *proximal position sense* [11, 31]. In this task, the robot passively moves the more-impaired limb to one of four targets positioned in a 12-cm square. The participant then actively mirror matches this position as precisely as possible with the less-impaired upper limb. Two parameters were calculated by the Kinarm software, namely the absolute error (i.e., mean of the absolute distance between the actual and matched position in the X and Y directions) and variability (i.e., root-sum-square of the standard deviations of the matched position in the X and Y directions). The ETH MIKE (Motor Impairment and Kinesthetic Evaluation) end-effector (Rehabilitation Engineering Laboratory, ETH Zurich, Zurich, Switzerland) measured position sense of the metacarpophalangeal joint or *distal position sense* [11, 32]. During the passive position sense task, the index finger of the participant is moved passively from a 0°-flexion position to one of 11 predefined positions, spaced every 2° between 10° and 30° of metacarpophalangeal flexion. Participants then indicate the perceived finger position on a tablet positioned above their hand. This results again in two task parameters representing the absolute error (i.e., mean of the absolute difference between the actual and indicated position of the index finger) and variability (i.e., standard deviation of the absolute error across all trials). Further details regarding the robotic assessments can be found elsewhere [11, 31].

2.2.2. Bimanual function

Different aspects of bimanual function were evaluated using both clinical measures of functional hand use and instrumented assessments of bimanual dexterity and coordination. Further details regarding the instrumented bimanual assessments can be found elsewhere [23, 33, 34].

Functional hand use was evaluated using the fifth version of the AHA and the Children's Hand-Use Experience Questionnaire (CHEQ 2.0). The AHA measures bimanual performance, which is defined as the spontaneous use of the more-impaired hand during bimanual tasks. Participants played a semi-structured board game that was video recorded [35]. Afterwards, 20 items related to upper limb function were scored on a 4-point scale. The CHEQ captures the subjective experience of the child's hand use during 27 bimanual daily life activities (http://www.cheq.se) [36]. The questionnaire was completed by the parents of the participants. It includes three subscales, that are all scored on a 4-point scale: (1) grasp effectiveness of the more-impaired hand (CHEQ-grip), (2) time required to complete the activity (CHEQ-time) and (3) the level of hindrance experienced by the more-impaired hand during task performance (CHEQ-feeling). For both assessments, raw scores are converted to a 0-100 logit-based scale, with higher scores indicating better performance.

Bimanual dexterity was assessed using the Tyneside Pegboard Test (TPT; Newcastle University, Newcastle upon Tyne, UK) [23, 24]. Participants were asked to transfer nine pegs as fast as possible from one board to an adjacent one, by passing it through an opening in a Perspex screen that was positioned between both boards. Completion times were recorded in two directions, namely from the more-impaired to the less-impaired hand (TPT_{MI-LI}) and from the less-impaired to the more-impaired hand (TPT_{LI-MI}).

Bimanual coordination was measured using the *box opening task*, where participants opened a box with the less-impaired hand and pressed a button inside with the more-impaired hand at a self-selected pace [25, 34]. Hand movements were recorded at a frequency of 120 Hz using three-dimensional electromagnetic motion sensors from Polhemus G4 (Polhemus, Colchester, Vermont, USA). Two bimanual parameters were calculated using MATLAB R2022a (The Mathworks Inc., Natick, MA, USA), namely the total movement time (i.e., average time needed to complete the task) and goal synchronization (i.e., the temporal coupling between the end of movement of both hands, normalized for total movement time). For both parameters, higher scores indicate poorer bimanual coordination.

Bimanual coordination was additionally assessed using the second level of the *Ball-on-Bar (BoB) task* on the Kinarm exoskeleton robot [31, 33]. Here, participants balanced a ball on a virtual bar, while reaching targets appearing on the screen. Three bimanual parameters, calculated by the Kinarm software, were selected based on the study of Decraene et al., namely bar tilt standard deviation (i.e., variability of the bar angle during the task), hand speed difference (i.e., difference between absolute hand speeds normalized by the mean hand speed) and hand path length bias (i.e., difference in hand path length between hands). These parameters have previously shown to be the most discriminative between children with uCP and typically developing children [33]. Lower scores on these parameters represent better bimanual coordination.

2.3. Statistical analysis

SPSS Statistics version 30.0 (IBM, Armonk, New York, USA) was used for all statistical analyses. Descriptive statistics were used to summarize the demographic information and clinical characteristics of the participants. The number of participants classified as having "intact", "impaired" or "absent" somatosensory function, based on the clinical assessments, was determined according to the cut-off values described above. For the robotic assessments, z-scores were computed to determine the number of participants with an impairment in proximal and/or distal position sense. Z-scores were calculated using the formula: $Z=(x-\bar{x})/S$, where x represents the individual score of the participant and $\bar{x}$ and S are respectively the mean and standard deviation of a control group consisting of 58 typically developing children (mean age 11y9mo (SD 2y9mo); 28 males)). Proximal and distal position sense were then classified as "intact" when the Z-scores of both parameters (i.e., absolute error and variability) were lower than 1.96, "impaired" when the Z-score of one of the two parameters was higher than 1.96 and "absent" when both Z-scores were higher than 1.96.

First, data normality was evaluated using Shapiro-Wilk tests. As the somatosensory data were not normally distributed, Spearman's rank correlations (r_s) were performed to map the relation between tactile registration, tactile perception, proprioception and bimanual function. A false discovery rate (adjusted p-value ≤ 0.05) for multiple testing correction was applied [37]. Correlation coefficients were interpreted as no or negligible (< 0.30), low (0.30–0.49), moderate (0.50–0.69), high (0.70–0.89) or very high (≥ 0.90) [38]. Secondly, to explore the extent to which measures of somatosensory function explain variability across measures of bimanual function, we performed multiple regression models with backward elimination. Multiple regressions models were made for the AHA and the feeling subscale of the CHEQ. The latter was selected as the level of hindrance experienced during bimanual tasks was expected to be most clinically relevant to children with uCP. For bimanual dexterity and bimanual coordination, parameters were selected based on the results of the correlation analyses, excluding the parameters with no significant correlation (p > 0.05) with any of the somatosensory assessments. Furthermore, we selected the parameters that showed to be the most discriminative between typically developing children and children with uCP in previous research, resulting in the following selection: the less-impaired to the more-impaired hand condition for the TPT, goal synchronization for the box opening task and hand path length bias for the BoB task of the Kinarm exoskeleton [23, 33, 34]. For the independent variables, a selection was also made based on clinical reasoning, as approximately one independent variable should be included per 10 participants [39]. More specifically, we selected at least one measure of each somatosensory modality, with the least interference of motor impairments expected and mostly reflecting the magnitude of somatosensory deficits rather than the consistency in performance across repetitions. This resulted in the following selection: Semmes-Weinstein monofilaments, two-point discrimination, movement sense and the absolute error of distal and proximal position sense. Multicollinearity between the independent variables was investigated using the variance inflation factor, with a value above 10 indicating multicollinearity. Outlier detection was based on the scatterplots of the standardized residuals, with values of more than 3.3 or less than − 3.3 being considered as outliers [40]. In the regression models for the parameters of bimanual coordination, some outliers were identified. Therefore, analyses were repeated removing one extreme outlier for the goal synchronization of the box opening task model and two extreme outliers for hand path length bias of the Kinarm BoB task model. For all the multiple regression analyses, the variance inflation factor ranged from 1.00 to 2.16, indicating low multicollinearity between the independent variables. Lastly, to study the relation between measures of functional hand use and instrumented measures of bimanual dexterity and coordination, Pearson (r) or Spearman's rank (r_s) correlations were performed, depending on the normality of the data. A false discovery rate (adjusted p-value ≤ 0.05) was again applied [37] and correlation coefficients were interpreted as no or negligible (< 0.30), low (0.30–0.49), moderate (0.50–0.69), high (0.70–0.89) or very high (≥ 0.90) [38].

3. RESULTS

3.1 Participants

A total of 61 children with uCP participated in this study. An overview of the demographic information and clinical characteristics is presented in Table 1. Technical issues with the robotic and instrumented assessments caused some missing data; distal and proximal position sense were missing in five participants, the TPT in 12 participants, the box opening task in 13 and the BoB task on the Kinarm exoskeleton in four participants.

Table 1. Demographic information and clinical characteristics of the participants.

		uCP (N=61), N (%)
Mean age (SD)		11y 11mo (3y 0mo)
Sex	Male	35 (57)
	Female	26 (43)
Side of cerebral palsy	Right-sided	32 (52)
	Left-sided	29 (48)
MACS	I	28 (46)
	II	24 (39)
	III	9 (15)
Tactile registration		
Semmes-Weinstein monofilaments	Intact *(0.008-0.07 grams)*	33 (54)
	Impaired *(0.16-300 grams)*	25 (41)
	Absent *(>300 grams)*	3 (5)
Tactile perception		
Stereognosis	Intact *(6/6 objects identified)*	18 (30)
	Impaired *(4-5/6 objects identified)*	28 (38)
	Absent *(≤3/6 objects identified)*	20 (32)
Two-point discrimination	Intact *(2-4 millimeters)*	34 (55)
	Impaired *(5-10 millimeters)*	18 (30)
	Absent *(>10 millimeters)*	9 (15)
Proprioception		
Movement sense	Intact *(3/3 small movements detected)*	45 (73)
	Impaired *(1/3 larger movements detected)*	12 (20)
	Absent *(no movement detected)*	4 (7)
Distal position sense	Intact *(both Z-scores <1.96)*	21 (38)
	Impaired *(only one Z-score >1.96)*	17 (30)
	Absent *(both Z-scores >1.96)*	18 (32)
Proximal position sense	Intact *(both Z-scores <1.96)*	23 (41)
	Impaired *(only one Z-score >1.96)*	7 (13)
	Absent *(both Z-scores >1.96)*	26 (46)

MACS: Manual Ability Classification System; mo: months; SD: standard deviation; y: years.

3.2 Relation between somatosensory and bimanual function

Table 2 shows the correlation coefficients between measures of tactile registration, tactile perception, proprioception and functional hand use, bimanual dexterity and bimanual coordination. Overall, several low to moderate correlations were found between somatosensory function and bimanual function, particularly for tactile perception and proprioception.

Children with worse **tactile registration** needed more time and were more hindered by their more-impaired hand when performing bimanual daily live activities (r_s=-0.320-(-0.408), p≤0.032), but no significant relationship was found with bimanual dexterity or coordination. For **tactile perception**, worse stereognosis and two-point discrimination was lowly to moderately related to worse functional hand use (r_s=-0.348-(-0.626), p≤0.023), slower performance of dexterous movements (r_s=-0.478-(-0.574), p<0.001) and worse bimanual coordination (|r_s|=0.357-0.501, p<0.022). Lastly, poorer **proprioceptive** accuracy was generally lowly related to reduced functional hand use (r_s=-0.236-(-0.493), p<0.113), bimanual dexterity (r_s=0.279-0.509, p<0.095) and with some parameters of bimanual coordination. Most notably, larger hand speed differences during the Kinarm BoB task related to worse movement sense (r_s=-0.315, p=0.036), distal (r_s=0.304-0.363, p<0.048) and proximal position sense (r_s=0.359-0.454, p<0.022). Larger distal position sense errors were further related to reduced goal synchronization in the box opening task (r_s=0.327, p=0.048), while worse proximal position sense related to larger bar tilt standard deviation and hand path length bias during the Kinarm BOB task (r_s=0.305-0.395, p<0.042).

Table 2. Spearman's rank correlation coefficients between measures of tactile registration, tactile perception, proprioception and bimanual function

			Tactile registration	Tactile perception		Proprioception				
			Semmes-Weinstein monofilaments	**Stereognosis**	**Two-point discrimination**	**Movement sense**	**Distal position sense - absolute error**	**Distal position sense - variability**	**Proximal position sense - absolute error**	**Prox posi sens varia**
Functional hand use	**AHA**		**-0.293**	***0.619***	***-0.626***	**0.335**	**-0.307**	**-0.320**	***-0.428***	***-0.4***
	CHEQ	***Grip***	-0.273	***0.531***	***-0.459***	**0.290**	**-0.338**	-0.266	**-0.356**	**-0.3**
		Time	**-0.320**	***0.460***	**-0.348**	**0.309**	**-0.308**	**-0.311**	**-0.388**	**-0.3**
		Feeling	***-0.408***	***0.541***	***-0.442***	**0.342**	-0.249	-0.236	**-0.415**	**-0.3**
Bimanual dexterity	**TPT**	***MI to LI***	0.229	***-0.478***	***0.479***	**-0.343**	0.279	**0.335**	**0.351**	***0.50***
		LI to MI	0.231	***-0.551***	***0.574***	**-0.356**	**0.328**	**0.345**	**0.364**	***0.47***
Bimanual coordination	**Box opening task**	***Total movement time***	0.294	-0.254	0.129	-0.289	0.174	0.082	0.156	0.09
		Goal synchronization	0.107	-0.217	0.182	-0.096	**0.327**	0.211	0.104	0.16
	Kinarm BoB	***Bar tilt standard deviation***	0.111	**-0.357**	0.256	-0.171	0.058	0.166	**0.305**	**0.39**
		Hand speed difference	0.260	***-0.501***	***0.499***	**-0.315**	**0.363**	**0.304**	**0.359**	***0.45***
		Hand path length bias	0.242	-0.199	0.114	-0.147	0.156	0.217	**0.362**	0.28

AHA: Assisting Hand Assessment; BoB: Ball-on-Bar task; CHEQ: Children's Hand-Use Experience Questionnaire; LI to MI: From the less-impaired to the more impaired hand; MI to LI: From the more-impaired to the less-impaired hand; TPT: Tyneside Pegboard Test.

Strength of correlation coefficients: light green = low, green = moderate, dark green = high.

Significance: bold = significant correlation with adjusted FDR-p≤0.05, bold italic = significant correlation with FDR-adjusted p≤0.01.

3.3 Variability in bimanual function explained by somatosensory function

Table 3 presents the results of the multiple regression analyses. **Two-point discrimination** emerged as the main determinant explaining a substantial proportion of variance in functional hand use and bimanual dexterity (R^2=0.167-0.292 p<0.001). **Proximal position sense** additionally determined functional hand use, as assessed with the AHA and CHEQ-feeling (R^2=0.050-0.113, p≤0.046), while **distal position sense** further explained bimanual dexterity (TPT_{LI-MI}, R^2=0.084, p=0.006). **Distal position sense** was also the only significant predictor of goal synchronization of the box opening task (R^2=0.115, p=0.006), while **proximal position sense** was identified for hand path length bias of the Kinarm BoB task, however, this model did not reach significance (**proximal position sense**: R^2=0.062, p=0.081).

Table 3. Overview of the final models of the multiple regressions analysis on distinct components of bimanual function.						
	Adjusted R²	Retained predictors	*p*-value	Unique R²	B (95% CI)	β
Functional hand use						
AHA	0.395	Two-point discrimination	<0.001	*0.292*	*-3.132 (-4.400; -1.864)*	-0.555
		Proximal position sense - absolute error	0.046	*0.050*	*-102.672 (-203.343; -2.001)*	-0.229
CHEQ-feeling	0.334	Two-point discrimination	<0.001	*0.167*	-2.419 (-3.780; -1.058)	-0.419
		Proximal position sense - absolute error	0.005	*0.113*	-158.315 (-266.369; -50.262)	-0.345
Bimanual dexterity						
TPT - LI to MI	0.576	Two-point discrimination	<0.001	*0.337*	*6.324 (4.140; 8.507)*	0.614
		Distal position sense - absolute error	0.006	*0.084*	*1.078 (0.335; 1.822)*	0.308
Bimanual coordination						
Box opening task - goal synchronization	0.094	Distal position sense - absolute error	0.024	*0.115*	*0.004 (0.001; 0.007)*	0.339
Kinarm BoB task - hand path length bias	0.043	Proximal position sense - absolute error	0.081	*0.062*	*0.268 (-0.034; 0.571)*	0.249

Adjusted R² = Degree of variance of the bimanual function assessment that is explained by the retained predictors; AHA: Assisting Hand Assessment; B: Unstandardized coefficient; β: Standardized coefficients; BoB: Ball-on-Bar task; CHEQ: Children's Hand-Use Experience Questionnaire; CI: Confidence interval; LI to MI: From the less-impaired to the more-impaired hand; TPT: Tyneside Pegboard Test; Unique R²: Degree of variance of the bimanual function assessment that is uniquely explained by one specific retained predictor.

3.4 Relation between functional hand use, bimanual dexterity and coordination

Correlation coefficients between measures of functional hand use, bimanual dexterity and coordination can be found in Table 4. Firstly, the **TPT** correlated moderately to highly with both measures of functional hand use (AHA: r_s=-0.682-(-0.757), *p*<0.001; CHEQ: r_s=-0.577-(-0.707), *p*<0.001), showing that worse bimanual dexterity was related to worse functional hand use. Secondly, the **box opening task** showed that worse goal synchronization and longer movement time were lowly related to worse functional hand use (r_s=-0.365-(-0.395), *p*≤0.016). Lastly, for the **BoB task of the Kinarm robot**, higher bar tilt standard deviation and hand speed difference were associated with worse functional hand use (r/r_s=-0.332-(-0.665), *p*≤0.016), while hand path length bias did not show any significant correlation (r_s=-0.161-(-0.263), *p*>0.061).

Table 4. Pearson and spearman's rank correlation coefficients between measures of functional hand use and measures of bimanual dexterity and coordination						
			Functional hand use			
			AHA	CHEQ-grip	CHEQ-time	CHEQ-feeling
Bimanual dexterity	**TPT**	**MI to LI**	***-0.682***	***-0.617***	***-0.577***	***-0.587***
		LI to MI	***-0.757***	***-0.707***	***-0.611***	***-0.647***
Bimanual coordination	**Box opening task**	**Total movement time**	**-0.376**	-0.276	-0.237	-0.208
		Goal synchronization	**-0.365**	**-0.395**	**-0.372**	**-0.367**
	Kinarm BoB	**Bar tilt standard deviation**	***-0.404***	**-0.332**	***-0.376***	**-0.344**
		Hand speed difference	***-0.665***	***-0.544***^{p}	***-0.522***^{p}	***-0.538***
		Hand path length bias	-0.161	-0.221	-0.263	-0.211

AHA: Assisting Hand Assessment; BoB: Ball-on-Bar task; CHEQ: Children's Hand-Use Experience Questionnaire; LI to MI: From the less-impaired to the more-impaired hand; MI to LI: From the more-impaired to the less-impaired hand; p: Pearson correlation coefficient; TPT: Tyneside Pegboard Test.

Strength of correlation coefficients: light green = low, green = moderate, dark green = high.

Significance: bold = significant correlation with adjusted FDR-p≤0.05, bold italic = significant correlation with FDR-adjusted p≤0.01.

4. DISCUSSION

In this study, we comprehensively evaluated somatosensory upper limb function and distinct components of bimanual function to obtain an improved understanding of their relation in children with uCP. We demonstrated low to moderate correlations, especially between tactile perception and proprioception with measures of functional hand use, bimanual dexterity and bimanual coordination. Regression analyses further indicated that two-point discrimination and robotic measurement of distal and proximal position sense explained part of the variability in bimanual function. Our findings underline the importance of comprehensive assessments of somatosensory function to further understand bimanual impairments.

First, our findings regarding tactile function closely align with earlier work by Poitras et al. (2021), who demonstrated that reduced higher-order tactile perception, particularly stereognosis and two-point discrimination, is consistently related to poorer bimanual performance in activities of daily living in children with (unilateral) CP, whereas tactile registration showed a generally weaker relation [15]. Similarly, in the present study, tactile perception was related to all measures of functional hand use and bimanual dexterity, while tactile registration was only weakly associated with perceived time and hinder during daily activities and showed no relationship with bimanual dexterity and bimanual coordination. Interestingly, the regression analyses further emphasized the important role of tactile perception, with two-point discrimination emerging as the strongest factor explaining a substantial proportion of variance in functional hand use and bimanual dexterity. The importance of tactile perception might be explained by the notion that higher-order tactile perception is essential in identifying object's characteristics, such as texture, shape and size, which is crucial to adjust grip strength and precise object manipulation [41]. In contrast, tactile registration reflects only the detection of a tactile stimulus and may be more easily compensated through visual feedback. Together, these findings add to the growing body of evidence that impairments in tactile perception, rather than tactile detection alone, limit the efficiency of bimanual actions even when overall task completion remains possible [15, 16].

Second, by using fine-grained robotic assessments of both distal and proximal position sense, our results showed several significant associations with bimanual function. Furthermore, proprioception was retained as one of the most important predictors in the different multiple regression models, underscoring its unique importance for bimanual function. Although no statistical comparison was performed, the observed associations were generally weaker than those found for tactile perception and appeared to be more task-dependent, which aligns with earlier research [15, 16]. More specifically, Poitras et al. (2021) suggested that robotics may improve the reliability of proprioceptive assessments, that often lack validity and protocol standardization in clinical practice, thereby enhancing insight into proprioceptive impairments and their impact on motor function [15]. Nevertheless, also using robotic proprioceptive assessments, the relation with bimanual function remains low [11, 32, 42]. As activities of daily living require movements of different upper limb joints simultaneously, methodological aspects of the current proprioceptive assessments might explain the weaker relationship found. Nevertheless, distal and proximal position sense contributed uniquely to several bimanual outcomes in the regression models. Distal position sense explained part of the variance in bimanual dexterity and goal synchronization during the box opening task, whereas proximal position sense explained additional variance in functional hand use. The TPT assessment and box opening task require fine motor function of the more-impaired hand to be able to place the peg accurately in the hole and specifically press a button inside the box [23, 24, 34]. Therefore, reduced distal position sense might cause stronger reliance on visual function, resulting in a longer task execution. While these bimanual assessments are performed relatively close to the body, assessments of functional hand use may additionally require reaching movements to handle objects positioned further away, potentially explaining the greater importance of proximal position sense. Taken together, these results suggest that proprioceptive impairments subtly constrain the precision and pace of bimanual function, being most related to tasks that demand continuous sensorimotor integration and movement corrections.

Lastly, we investigated associations between distinct components of bimanual function, namely functional hand use, bimanual dexterity and bimanual coordination. Functional hand use showed moderate to strong correlations with bimanual dexterity, consistent with earlier literature [23]. These associations may be attributed to the fact that both functional hand use and bimanual dexterity assessments rely extensively on the grasping ability of the more-impaired hand [23, 24, 35]. In contrast, associations between functional hand use and bimanual coordination varied from negligible to moderate across parameters. This finding confirms that bimanual coordination is a multifaceted process that additionally reflects movement strategies and movement quality, components that are often not evaluated using clinical assessments of functional hand use [22]. Nevertheless, parameters reflecting temporal interlimb differences, such as hand speed difference, goal synchronization or bar tilt standard deviation, showed most association with functional hand use. This finding suggests that temporal coupling of both hands is particularly relevant for daily activities. In contrast, spatial alignment (hand path length bias) or overall task performance (total movement time) seem not to be related to functional hand use, possibly because these aspects can be more easily compensated for without substantially affecting task performance. Interestingly, this pattern may also explain why somatosensory function appears to be particularly relevant for tasks requiring rapid and spontaneous movements. In such tasks, reliance on compensatory mechanisms, using the less-impaired limb, visual function or cognition, is limited. Instead, more automated and unconscious sensorimotor processes predominate. As accurate integration of somatosensory input is necessary for fine-grained sensorimotor control, reduced somatosensory function can directly constrain the effectiveness and speed of hand use [1, 2].

Nevertheless, some limitations of this study should be recognized. First, technical difficulties with the robotic and instrumented assessment resulted in some missing data and therefore, not all participants could be included in the analyses. However, as the pattern of missing data was random, the analyses remained unbiased [43]. Second, future studies with larger sample sizes could focus on combining several explanatory factors, such as cognition, attention, but also the presence of mirror movements and visual function, to further improve our clinical insight in the variability of bimanual function. It should also be recognized that bimanual function, unimanual motor capacity and somatosensory function likely interact in complex and reciprocal ways. Future longitudinal studies are warranted to better characterize these relationships and clarify their directionality. Lastly, we performed a comprehensive somatosensory test battery, including assessments of tactile registration, tactile perception and proprioception. Nevertheless, the selected tactile assessments did not evaluate the temporal and modality-specific dimensions of tactile perception and no somatosensory evaluation of the less impaired upper limb was included, although previous research indicated that somatosensory impairments can be present in both upper limbs [11, 13, 17]. Moreover, methodological differences in the proprioceptive assessments used, such as the plane of movement and number of joints simultaneously assessed, might impact the correlations found in this study.

5. CONCLUSIONS

When performing bimanual tasks, somatosensory information is important to synchronize the movements of both hands and ensure successful task performance. Although tactile and proprioceptive impairments are common in children with uCP, the relation with distinct aspects of bimanual function has not fully been examined. This study demonstrated that higher-order tactile perception and robotic assessment of proprioception are related to bimanual function, with the strongest associations for functional hand use and bimanual dexterity. In contrast, relationships with bimanual coordination were more parameter-specific, potentially reflecting differences in task demands, compensatory strategies and the potential role of other factors such as cognition and visual function. Together, these findings highlight that distinct aspects of bimanual function rely on different sensorimotor processes and underscore the importance of comprehensively assessing tactile perception and proprioception in clinical practice. Further research should examine whether targeting somatosensory function may offer opportunities to optimize bimanual function, particularly for tasks requiring precise object manipulation and dexterous hand use.

Abbreviations

CP: Cerebral palsy

uCP: Unilateral cerebral palsy

AHA: Assisting Hand Assessment

CHEQ: Children's Hand-Use Experience Questionnaire

TPT: Tyneside Pegboard Test

$TPT_{MI\text{-}LI}$: Tyneside Pegboard Test from the more impaired to the less impaired hand

$TPT_{LI\text{-}MI}$: Tyneside Pegboard Test from the less impaired to the more impaired hand

BoB: Ball-on-Bar

Declarations

ACKNOWLEDGEMENTS

We would like to express our appreciation to all children and families for their participation in this study. We additionally thank Dr. Monica Crotti and Dr. Lisa Decraene for their efforts in the recruitment and assessment of participants.

FUNDING

This work was supported by the Flemish Research Foundation (FWO-Vlaanderen) under an FWO project (G0C4919N) and an FWO research fellowship to LK (11PP224N).

DECLARATIONS OF INTEREST

The authors report there are no competing interests to declare.

DATA AVAILABILITY

Detailed research data related to this manuscript are available upon reasonable request to the corresponding author. The data are not publicly available due to participant privacy restrictions.

Declarations of interest: None

References

1. Machado S, Cunha M, Velasques B, Minc D, Teixeira S, Domingues CA et al (2010) Sensorimotor integration: Basic concepts, abnormalities related to movement disorders and sensorimotor training-induced cortical reorganization. Rev Neurol 51(7):427–436
2. Edwards LL, King EM, Buetefisch CM, Borich MR (2019) Putting the sensory into sensorimotor control: The role of sensorimotor integration in goal-directed hand movements after stroke. Front Integr Neurosci 13:16. https://doi.org/10.3389/fnint.2019.00016
3. Delhaye BP, Long KH, Bensmaia SJ (2018) Neural Basis of Touch and Proprioception in Primate Cortex. Compr Physiol 8:1575–1602. https://doi.org/10.1002/cphy.c170033
4. Rosenbaum P, Paneth N, Leviton A, Goldstein M, Bax M, Damiano D et al (2007) A report: the definition and classification of cerebral palsy. Dev Med Child Neurol Suppl 109:8–14
5. Brun C, Traverse É, Granger É, Mercier C (2021) Somatosensory deficits and neural correlates in cerebral palsy: a scoping review. Dev Med Child Neurol 63:1382–1393. https://doi.org/10.1111/dmcn.14963
6. Knijnenburg ACS, Steinbusch CVM, Janssen-Potten YJM, Defesche A, Vermeulen RJ (2023) Neuro-imaging characteristics of sensory impairment in cerebral palsy; a systematic review. Front Rehabil Sci 4:1084746. https://doi.org/10.3389/fresc.2023.1084746

7. Himmelmann K, Uvebrant P (2018) The panorama of cerebral palsy in Sweden part XII shows that patterns changed in the birth years 2007–2010. Acta Paediatrica. Int J Paediatr 107(3):462–468. https://doi.org/10.1111/apa.14147
8. McLean B, Taylor S, Valentine J, Carey L, Thornton A, Elliott C (2021) Somatosensory discrimination impairment in children with hemiplegic cerebral palsy as measured by the sense_assess© kids. Aust Occup Ther J 68:317–326. https://doi.org/10.1111/1440-1630.12729
9. Auld ML, Boyd R, Moseley GL, Ware R, Johnston LM (2012) Tactile function in children with unilateral cerebral palsy compared to typically developing children. Disabil Rehabil 34:1488–1494. https://doi.org/10.3109/09638288.2011.650314
10. Jovellar-Isiegas P, Cuesta García C, Jaén-Carrillo D, Palomo-Carrión R, Peña Alonso C, Roche-Seruendo LE (2023) Somatosensation and motor performance in the less-affected and more-affected hand of unilateral cerebral palsy children: a cross-sectional study. Disabil Rehabil 45(21):3500–3510. https://doi.org/10.1080/09638288.2022.2127938
11. Kleeren L, Mailleux L, Crotti M, Decraene L, Verheyden G, Lambercy O et al (2026) Unraveling tactile and proprioceptive upper limb function in children with unilateral cerebral palsy: a combination of robotic and clinical assessments. Disabil Rehabil 48(5):1369–1390. https://doi.org/10.1080/09638288.2025.2556944
12. Dunn W, Griffith JW, Morrison TM, Tanquary J, Sabata D, Victorson D, Carey LM, Gershon RC (2013) Somatosensation assessment using the NIH Toolbox. Neurology 80(11):41–44. https://doi.org/10.1212/WNL.0b013e3182872c54
13. Auld ML, Boyd RN, Moseley GL, Johnston LM (2011) Tactile assessment in children with cerebral palsy: A clinimetric review. Phys Occup Ther Pediatr 31:413–439. https://doi.org/10.3109/01942638.2011.572150
14. Klingner CM, Witte OW. Somatosensory deficits. In: Handbook of. Clinical. Neurology, vol. 151, Elsevier BV (2018) pp. 185–206. https://doi.org/10.1016/B978-0-444-63622-5.00009-7
15. Poitras I, Martinie O, Robert MT, Campeau-Lecours A, Mercier C (2021) Impact of sensory deficits on upper limb motor performance in individuals with cerebral palsy: A systematic review. Brain Sci 11(6):744. https://doi.org/10.3390/brainsci11060744
16. Santana CAS, dos Santos MM, de Campos AC (2022) Interrelationships of Touch and Proprioception with Motor Impairments in Individuals with Cerebral Palsy: A Systematic Review. Percept Mot Skills 129(3):570–590. https://doi.org/10.1177/00315125221093904
17. Sel SA, Arat M, Erdoğanoğlu Y (2026) Activity and Participation in Adolescents With Hemiplegic Cerebral Palsy: The Role of Upper Extremity Dexterity and Proprioception Within the ICF Framework. Percept Mot Skills. https://doi.org/10.1177/00315125261437312
18. Horváth Á, Ferentzi E, Schwartz K, Jacobs N, Meyns P, Köteles F (2023) The measurement of proprioceptive accuracy: A systematic literature review. J Sport Health Sci 12(2):219–225. https://doi.org/10.1016/j.jshs.2022.04.001
19. Hillier S, Immink M, Thewlis D (2015) Assessing Proprioception: A Systematic Review of Possibilities. Neurorehabil Neural Repair 29(10):933–949. https://doi.org/10.1177/1545968315573055
20. Green D (2018) The Tyneside Pegboard Test: balancing clinical utility against ecological validity. Dev Med Child Neurol 60:224. https://doi.org/10.1111/dmcn.13678
21. Riquelme I, Arnould C, Hatem SM, Bleyenheuft Y (2019) The Two-Arm Coordination Test: Maturation of Bimanual Coordination in Typically Developing Children and Deficits in Children with Unilateral Cerebral Palsy. Dev Neurorehabil 22(5):312–320. https://doi.org/10.1080/17518423.2018.1498552
22. Swinnen SP, Gooijers J (2015) Bimanual Coordination. Brain Mapping: An Encyclopedic Reference, vol 2. Elsevier Inc., pp 475–482. https://doi.org/10.1016/B978-0-12-397025-1.00030-0.
23. Decraene L, Feys H, Klingels K, Basu A, Ortibus E, Simon-Martinez C et al (2021) Tyneside Pegboard Test for unimanual and bimanual dexterity in unilateral cerebral palsy: association with sensorimotor impairment. Dev Med Child Neurol 63:874–882. https://doi.org/10.1111/dmcn.14858
24. Basu AP, Kirkpatrick EV, Wright B, Pearse JE, Best KE, Eyre JA (2018) The Tyneside Pegboard Test: development, validation, and observations in unilateral cerebral palsy. Dev Med Child Neurol 60:314–321. https://doi.org/10.1111/dmcn.13645
25. Rudisch J, Butler J, Izadi H, Zielinski IM, Aarts P, Birtles D et al (2016) Kinematic parameters of hand movement during a disparate bimanual movement task in children with unilateral Cerebral Palsy. Hum Mov Sci 46:239–250. https://doi.org/10.1016/j.humov.2016.01.010
26. Lowrey R (2014) A Novel Robotic Task for Assessing Impairments in Bimanual Coordination Post-Stroke. Int J Phys Med Rehabil. https://doi.org/10.4172/2329-9096.s3-002. s3
27. Koman LA, Williams RMM, Evans PJ, Richardson R, Naughton MJ, Passmore L et al (2008) Quantification of upper extremity function and range of motion in children with cerebral palsy. Dev Med Child Neurol 50:910–917. https://doi.org/10.1111/j.1469-8749.2008.03098.x
28. Auld ML, Ware RS, Boyd RN, Moseley GL, Johnston LM (2012) Reproducibility of tactile assessments for children with unilateral cerebral palsy. Phys Occup Ther Pediatr 32(2):151–166. https://doi.org/10.3109/01942638.2011.652804
29. Bell-Krotoski JA, Fess EE, Figarola JH, Hiltz D (1995) Threshold Detection and Semmes-Weinstein Monofilaments. J Hand Ther 8(2):155–. https://doi.org/10.1016/s0894-1130(12)80314-0. 62
30. Klingels K, De Cock P, Molenaers G, Desloovere K, Huenaerts C, Jaspers E et al (2010) Upper limb motor and sensory impairments in children with hemiplegic cerebral palsy. Can they be measured reliably? Disabil Rehabil 32(5):409–416. https://doi.org/10.3109/09638280903171469
31. BKIN Technologies Ltd (2021) Dexterit-E Explorer 3.9 User's Guide. Canada, Ontario
32. Zbytniewska-Mégret M, Decraene L, Mailleux L, Kleeren L, Kanzler CM, Gassert R et al (2022) Reliable and Valid Robotic Assessments of Hand Active and Passive Position Sense in Children With Unilateral Cerebral Palsy. Front Hum Neurosci 16:895080. https://doi.org/10.3389/fnhum.2022.895080
33. Decraene L, Orban de Xivry JJ, Kleeren L, Crotti M, Verheyden G, Ortibus E et al (2023) In-depth quantification of bimanual coordination using the Kinarm exoskeleton robot in children with unilateral cerebral palsy. J Neuroeng Rehabil 20:154. https://doi.org/10.1186/s12984-023-01278-6

34. Mailleux L, Decraene L, Kalkantzi A, Kleeren L, Crotti M, Campenhout A, Van et al (2024) Spatiotemporal coordination in children with unilateral cerebral palsy: Insights from a bimanual goal-directed task. Eur J Paediatr Neurol 53:73–87. https://doi.org/10.1016/j.ejpn.2024.10.003
35. Louwers A, Beelen A, Holmefur M, Krumlinde-Sundholm L (2016) Development of the Assisting Hand Assessment for adolescents (Ad-AHA) and validation of the AHA from 18 months to 18 years. Dev Med Child Neurol 58:1303–1309. https://doi.org/10.1111/dmcn.13168
36. Sköld A, Hermansson LN, Krumlinde-Sundholm L, Eliasson AC (2011) Development and evidence of validity for the Children's Hand-use Experience Questionnaire (CHEQ). Dev Med Child Neurol 53:436–442. https://doi.org/10.1111/j.1469-8749.2010.03896.x
37. Benjamini Y, Hochberg Y (1995) Controlling the False Discovery Rate: A Practical and Powerful Approach to Multiple Testing. J R Stat Soc 57:289–300. https://doi.org/10.1111/j.2517-6161.1995.tb02031.x
38. Hinkle DE, Wiersma W, Jurs SG, Mifflin H (1990) Applied Statistics for the Behavioral Sciences. J Educ Stat 15(1):84–87. https://doi.org/10.2307/1164825
39. Harrell FE, Lee KL, Mark DB (1996) Prognostic/Clinical Prediction Models: Multivariable Prognostic Models: Issues in Developing Models, Evaluating Assumptions and Adequacy, and Measuring and Reducing Errors. Statist Med 15:361–387. https://doi.org/10.1002/(SICI)1097-0258(19960229)15:4%3C361::AID-SIM168%3E3.0.CO;2-4
40. Hair JF, Black WC, Babin BJ, Anderson RE (2019) Multivariate data analysis, 8th edn. Cengage Learning EMEA, United Kingdom
41. Saal HP, Birznieks I, Johansson RS (2025) Fingertip viscoelasticity enables human tactile neurons to encode loading history alongside current force. eLife 12:RP89616. https://doi.org/10.7554/elife.89616
42. Kuczynski AM, Dukelow SP, Semrau JA, Kirton A (2016) Robotic quantification of position sense in children with perinatal stroke. Neurorehabil Neural Repair 30(8):762–772. https://doi.org/10.1177/1545968315624781
43. Kang H (2013) The prevention and handling of the missing data. Kor J Anesthesiol 64:402–406. https://doi.org/10.4097/kjae.2013.64.5.402