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Motor patterns of the impaired upper limb in children with unilateral cerebral palsy performing bimanual tasks

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ABSTRACT

Background

Upper limb movement patterns have not yet been identified in bimanual conditions despite the difficulties children with unilateral cerebral palsy have performing bimanual activities. The aim was to identify specific motor patterns from kinematic deviations during bimanual tasks in this population.

Methods

Twenty children with unilateral cerebral palsy and 20 age-matched, typically developing children performed the five tasks of a 3D bimanual protocol. To evaluate upper limb kinematic deviations, 10 Arm Variable Scores were calculated for the affected /non-dominant upper limb of each participant for each task. Sparse K-means cluster analysis was applied to the 50 Arm Variable Scores of all the children to identify motor patterns and determining variables. Clinical tests of impairment (muscle strength, selectivity, spasticity) and function (Assisting hand assessment, Abilhand-Kids) were compared between the clusters obtained.

Findings

Three different motor patterns were identified using the data from all the children: mild, proximal-distal and proximal-distal with trunk. The most important cluster determinants were the Arm Variable Scores for pronation-supination and wrist extension. In the cerebral palsy group, scores of impairments ($p < .01$) and function (Assisting Hand Assessment [$p < .001$] and Abilhand-Kids [$p = .004$]) differed for each motor pattern. Supination and wrist extension deviations differed significantly between the groups ($p < .001$).

Interpretation

During performance of bimanual tasks, children with unilateral cerebral palsy used distinct motor patterns that each corresponded to a specific clinical profile. Elbow-wrist deviations were the largest and most decisive and were specific to the cerebral palsy group: they should be the target of interventions to enhance bimanual function.

ClinicalTrials.gov identifier: NCT03888443

KEYWORDS

children; cerebral palsy; motion analysis; upper limb; bimanual; motor pattern

1. INTRODUCTION

Children with unilateral cerebral palsy (uCP) have difficulty with bimanual interaction and coordination. Since most activities of daily living are bimanual, assessing movement limitations in bimanual conditions [1,2] would help to identify the impairments that negatively impact the performance of daily life activities [3]; therapies and interventions could then be tailored accordingly. However, to date, bimanual assessments remain semi-quantitative and do not include kinematics. To this purpose, a bimanual 3D motion analysis (3DMA) protocol, 'Be An Airplane Pilot' (BE-API) was developed and validated to assess the kinematics of the impaired upper limb (UL) of children with uCP [4,5]. It consisted of a five-task protocol integrated into a game scenario. Each task evaluated specific impaired UL joint angle during bimanual tasks: the five tasks together evaluated all the UL joint angles.

Few studies have attempted to classify overall UL movement patterns in children with uCP; furthermore, movement patterns have only been evaluated during unimanual and not bimanual tasks [6–8]. Such a classification presents a challenge because of the complexity of UL movements and the necessity to account for the large clinical heterogeneity within this population. However, clinicians would have a better understanding of a child's functional limitations if they could identify the contribution of each joint to the overall UL movement pattern, as well as the movement specificities of children with CP compared to typically developing children (TDC). In addition, it would be useful to determine if specific movement patterns during bimanual tasks were associated with certain clinical profiles: relationships between clinical assessments and UL kinematics have previously been reported [4,9]. This information would offer valuable insights into abnormal movement that would help to tailor impairment-based UL treatments.

Our hypothesis was that distinct patterns of UL movement could be identified in children with uCP performing bimanual tasks. The main objective of this study was therefore to use UL joint deviation data recorded during bimanual tasks in children with uCP and TDC to identify motor patterns, and to identify the kinematic variables which were the most discriminant for each pattern. The second objective was to determine if there were differences in clinical ratings of impairment and function between each motor pattern. The third objective was to compare kinematic movement deviations between children with uCP and TDC to identify those which were specific to the uCP group.

32

33 2. METHODS

34

35 2.1 Participants

36 This study used data from the validation study of the “Be An Airplane Pilot 2.0” (BE-API 2.0)
37 protocol [4]. Twenty children with uCP were recruited from the Physical Medicine and
38 Rehabilitation Department of Rennes University Hospital (France) between February and June
39 2019. Children aged 6 to 17 years with sufficient UL movement (reach and grasp) to perform the
40 protocol tasks (Manual Ability Classification System (MACS) [10] level I to III) were prospectively
41 included. Children with severe cognitive or visual disturbances, UL pain, previous UL surgery or
42 who had undergone botulinum toxin injections less than three months previously were excluded.
43 Twenty age-matched TDC were included for comparison. Approval was obtained from the ethical
44 committee Ouest II from Angers. All the parents and children received oral and written information
45 about the study and non-opposition to the use of the data was collected.

46 2.23D-Motion analysis procedure

47 The BE AP 2.0 protocol was performed by both the children with uCP and the TDC. This protocol
48 is the first to propose an overall assessment of UL degrees of freedom (DoF) during bimanual
49 tasks with 3D kinematic recordings, and has been found to have excellent psychometric
50 properties for validity and reliability in both children with uCP and TDC [4].

51 The BE-API 2.0 protocol involves 3D kinematic recording of five bimanual tasks performed in a
52 game scenario [4]: flying an aeroplane. It involves the manipulation of a 2-handed joystick, turbo,
53 shifter, dashboard, box and buzzer. Each task (“flying mission”) is designed to evaluate one or
54 two UL DoF in particular. Task 1 “flying over mountains” consists of using both hands to push the
55 wheel down and pull it back up (elbow extension and wrist adduction). Task 2 “slaloming”
56 consists of rotating the wheel with the affected hand 90° upwards then 90° downwards while
57 pressing the turbo with the dominant hand (shoulder rotations). Task 3 “hooking the luggage”
58 consists of hanging a magnet on a dashboard as high as possible while the other hand keeps the
59 wheel horizontal (shoulder plane of elevation and elevation). Task 4 “opening the door” consists
60 of hanging a magnet on a dashboard as high as possible while the other hand keeps the wheel
61 horizontal (wrist extension). Task 5 “refueling” consists of pressing the buzzer with the dominant
62 hand while the affected hand supinates to catch a gas coin and places it on the gas tank
63 (supination). For the TDC group, the non-dominant hand was used to perform the tasks which
64 were performed by the affected hand in the uCP group. More details of the set-up and tasks are
65 provided in Cacioppo et al. [4] and Supplementary Material 1.

66 In this protocol, bimanual tasks are considered as the simultaneous use of both hands, either to
67 perform a symmetrical (task 1) or asymmetrical (tasks 2, 3, 4 et 5) movement. In asymmetrical
68 tasks, the movement of interest was only performed by the impaired (non-dominant) UL while the
69 dominant UL was involved in a different, simultaneous movement to accomplish the task.

70 **2.3 Data collection**

71 Kinematic data were recorded with a 10 camera VICON® system (sampling 100 Hz, Oxford
72 Metrics, UK). Twenty-six 9mm markers were fixed to the trunk, arms, forearms and hands
73 according to the recommendations of the International Society of Biomechanics (ISB) [11]
74 (Supplementary Material 2). Shoulder (rotations, plane of elevation, elevation), elbow (flexion-
75 extension, pronation-supination) and wrist (flexion-extension, abduction-adduction) kinematics
76 were calculated for each task using the Euler sequences recommended by the ISB [11]. The
77 shoulder joint was defined as the “thoraco-humeral joint” and its centre was estimated using a
78 functional method [12,13].

79 **2.4 Data analysis**

80 Arm Profile Scores (APS) and Arm Variable Scores (AVS) were calculated for each task, as
81 described in Jaspers et al. [14], except for scapula movements. Each angular waveform was
82 time-normalized between 0 and 100%. Then, AVS were calculated using the root mean square
83 error (RMSE) between the point-by-point comparison of each joint angle of a child and the mean
84 value for the same joint angle from the database of the 20 TDC age-matched children included in
85 the study. Therefore, a total of 10 AVS were calculated for each task: trunk (flexion/extension,
86 abduction/adduction, axial rotation), shoulder (plane of elevation, elevation, rotation), elbow
87 (flexion/extension, pronation/supination) and wrist (flexion/extension, abduction/adduction). The
88 APS corresponds to the mean RMSE of all 10 joint angles and is used to measure the total
89 amount of movement deviation in each task. The 10 AVS and APS were presented together in a
90 bar chart representing the Arm Movement Analysis Profile (A-MAP) (Figure 3). All the data were
91 processed with Matlab® (MathWorks, Natick, MA, USA).

92 **2.5 Clinical assessments**

93 On the same day as they performed the BE API 2.0 protocol, each child with uCP also underwent
94 an assessment of impairment (muscle strength, selectivity and spasticity) and two functional
95 evaluations (Assisting Hand Assessment (AHA) [15] and the ABILHAND-Kids [16])
96 (Supplementary Material 3).

97 Muscle strength, selectivity and spasticity were evaluated for 16 muscle groups and individual
98 muscles by experienced physiotherapists (Supplementary Material 4). Muscle strength was
99 evaluated using the Medical Research Council scale (MRC) [17], a six-point ordinal scale from 0

100 to 5 in which 0 indicates no muscle contraction and 5 indicates normal strength. A composite
101 strength score was defined as the sum of the muscle weakness scores (total score: 0-80). Muscle
102 selectivity was evaluated using selective motor control (SMC) [18], a five-point ordinal scale from
103 0 to 2, in increments of 0.5, in which a score of 2 corresponded to normal selectivity. A composite
104 selectivity score was defined as the sum of the muscle selectivity scores (total score: 0-32).
105 Muscle spasticity was evaluated with the Modified Ashworth Scale (MAS) [19], a six-point ordinal
106 scale, rating from 0 to 4 (possible scores: 0,1,1+,2,3,4). A score of 0 represents normal muscle
107 tone, whereas a score of 4 corresponds to no possible movement due to rigidity. A composite
108 spasticity score, rated from 0 to 5, was defined as the sum of MAS scores for each child (total
109 score: 0-80 [16 muscles x 5 levels]).

110 The Assisting Hand Assessment (AHA) [15], was used to evaluate bimanual performance. It
111 involves rating the spontaneous use of the impaired UL from a video recording of bimanual tasks
112 performed during a play-session. The total score ranges from 0 to 100 AHA-units, where 100
113 AHA-units corresponds to normal spontaneous use of the impaired hand. It was rated by a
114 trained occupational therapist. The Abilhand-kids questionnaire [16] was used to assess manual
115 performance in daily activities. It involves the rating of 21 mostly bimanual activities by the
116 parents. The score is expressed in %-logits and higher scores correspond to higher manual
117 ability.

118 **2.6 Statistical methods**

119 Sparse K-means (SK-means) cluster analysis [20] was applied to the AVS of all the children in
120 order to define UL motor patterns, following the recent method applied by Abbasi et al. for gait
121 analysis [21], using R studio®. In contrast with classical K-means analysis, this method
122 simultaneously identifies both clusters and decisive variables, and thus yields results that are
123 more easily interpreted clinically. Variables were inputted in the clustering process with no
124 prejudice of their influence. SK-means analysis uses a LASSO-type penalty to select the
125 variables which contribute to maximize the between-cluster distance. This penalty estimates the
126 weighting of each variable in this maximization problem. Then, the relative weighting (RW) for
127 variable i was calculated as $w_i / \sum w_i \times 100$. All AVS were considered independently for each of the
128 5 tasks in the clustering. The optimal number of clusters was determined with the elbow method
129 [22].

130 The results of the clinical tests of impairment (muscle strength, selectivity and spasticity) and
131 function (MACS level, AHA and Abilhand-Kids) were then compared between the resulting motor
132 patterns using a one-way ANOVA or Kruskal-Wallis test according to the data distribution.

133 AVS were compared between groups using a repeated measures ANOVA (mixed model) with
134 uCP/TDC as a between-subject factor and AVS and tasks as within-subjects factors. APS were

135 also compared between groups using a repeated measures ANOVA. A post-hoc analysis with a
136 Bonferroni correction was applied on significant results. All the statistical tests were performed
137 with a two-tailed significance level of 5% (using Statistica® 13.0 (StatSoft, TIBCO Software Inc.)).

138 **3. RESULTS**

139

140 **3.1 Participants (Figure 1)**

141 Twenty children with uCP were enrolled in this study (mean age 11.4 (± 3.01) years; 16 girls; 10
142 right side impairment). Ten children had MACS level I, 5 MACS level II and 5 MACS level III.
143 Mean MRC score was 58.9 (± 12.1), SMC score was 25.2 (± 5.8), and MAS score was 2.45 (± 4.1).
144 Mean AHA score was 67 (± 17) AHA-units and mean ABILHAND-Kids score was 74 (± 12.3) %-
145 logits (one missing). Twenty age-matched TDC were included for comparison (mean age 10.7
146 (± 2.96) years; 15 boys; 18 left side non-dominant).

147

148 **3.2 Motor patterns identified from kinematic deviation (AVS) clusters**

149 **3.2.1 SK-means clustering (Figure 2)**

150 The sensitivity analysis for the SK-means clustering algorithm indicated that the optimal number
151 of clusters for the dataset (40 children) was 3. When the data from the entire protocol (i.e. all
152 tasks) were pooled, all TDC were classified as Pattern 1, except one child.

153

154 **3.2.2 Description of the three motor patterns (Figure 2.1 and Table 1)**

155 **3.2.2.1 Pattern 1 – Mild deviations**

156 Pattern 1 included 9 children with uCP and 19 TDC. Deviations were generally small and the
157 most deviated DoF differed for each task. Elbow pronation-supination was persistently more
158 deviated than the other DoF, except in Task 4. Mean AVS was 9° (2.14-17.12°).

159 **3.2.2.2 Pattern 2 – Proximal-distal deviations**

160 Pattern 2 included 8 children with uCP and 1 TDC. AVS were higher than for Pattern 1 in each
161 task: mean AVS was 14.5° (1.9- 41.2°). The largest deviations were both distal and proximal
162 (elbow pronation-supination, wrist extension, elbow extension, wrist adduction, shoulder plane of
163 elevation, rotations). Elbow pronation-supination was persistently more deviated than the other
164 DoF except in Task 4. Wrist adduction AVS was higher than in Patterns 1 and 3 (Supplementary
165 Material 5).

166 **3.2.2.3 Pattern 3 – Proximal-distal and trunk deviations**

167 Pattern 3 included 3 children with uCP. The largest deviations were for distal joints (elbow
168 extension, elbow pronation-supination and wrist extension). Shoulder rotations, plane of
169 elevation, elevation and rotations were largely deviated especially for Tasks 2 and 3 which
170 particularly involved shoulder movement. Elbow pronation-supination was persistently more

171 deviated than the other DoF except in Task 4. Trunk AVS were higher than in Patterns 1 and 2,
172 especially trunk rotation AVS. Mean AVS was 23.9° (2.9-102.8°) (Supplementary Material 5).

173

174 **3.2.3 Cluster determinants (Figure 2.2)**

175 From the 50 variables included in the cluster analysis, 17 accounted for more than 80% of the
176 total weights of the variables. The AVS for each task all contributed to the final clustering
177 decision. The most decisive AVS were elbow pronation-supination (tasks 1,2,3,5; RW=5.19-
178 22.7%), wrist extension (all tasks; RW=2.72-11.11%) and elbow extension (all tasks; RW=1.16-
179 1.71%).

180

181 **3.3 Comparison of clinical profiles between motor patterns (Table 2)**

182

183 Significant differences were found for MACS level ($p<.001$), AHA score ($p<.001$), Abilhand-Kids
184 ($p=0.009$), muscle strength ($p=<.001$), selectivity ($p<.001$) and spasticity ($p<.001$) between the
185 three clusters. In Pattern 1, the uCP group had higher mean AHA and Abilhand-Kids scores,
186 greater strength and selective control and less spasticity. In Pattern 3, they had lower mean AHA
187 and Abilhand-Kids scores, lower strength and selectivity and more spasticity.

188

189 **3.4 Comparison of kinematics between children with uCP and TDC (Figure 3)**

190

191 APS and AVS were significantly higher in the uCP group (mean difference of 7.60°, $p<0.001$, and
192 5.31°, $p<0.001$ respectively). There was a significant interaction between AVS and group
193 ($p<0.001$), and between AVS and task ($p<0.001$), and a significant main effect of group and task
194 on AVS ($p<0.001$). In the post hoc analysis, the children with uCP had significantly greater elbow
195 pronation-supination (15.6°, $p<0.001$) and wrist extension (12.2°, $p<0.001$) deviations than the
196 TDC.

197

198

4. DISCUSSION

200 This original study mined kinematic data using cluster analysis and identified three patterns of UL
201 kinematic deviations in children with uCP performing bimanual tasks. The variables which
202 particularly influenced the clusters were elbow pronation-supination and wrist extension
203 deviations. Clinical ratings of impairment and function differed significantly between the three
204 motor patterns, suggesting a relationship between motor pattern and clinical severity. The
205 children with uCP had significantly greater elbow pronation-supination and wrist extension
206 deviations than the TDC, indicating these deviations were specific to the uCP group.

207 The results of this study demonstrated that the kinematic deviations of the children with uCP
208 could be classified into three different motor patterns. To our knowledge, only the study by Rouafi
209 et al. [7] attempted to classify UL kinematic movements in children with uCP using clustering.
210 Using both kinematic and EMG variables, they identified four clusters which were related to the
211 MACS level. However, their analysis only included elbow flexion-extension and pronation-
212 supination kinematics. In the present study, children with Pattern 1 were able to adapt the
213 recruitment of each DoF according to the task, whereas those with Pattern 3 had large deviations,
214 especially of the elbow and wrist, across all tasks. The trunk was also often more deviated in this
215 pattern, suggesting that the more severe distal impairments induced more pronounced proximal
216 compensations [5,23–25]. The finding that elbow pronation-supination and wrist extension
217 particularly discriminated between motor patterns revealed that distal motor impairments strongly
218 influence the overall UL movement pattern in children with uCP. Distal impairments must
219 therefore be more largely considered when analyzing bimanual performance in children with uCP.
220 This information could help clinicians to make treatment decisions and to evaluate the
221 effectiveness of interventions [2,26,27].

222 The three motor patterns identified corresponded to three distinct levels of impairment and
223 function in children with uCP, showing a link between pattern-type and CP-severity. Relationships
224 have previously been found between the AHA score and kinematic deviations during both
225 unimanual [5,24] and bimanual tasks [4]. This supports the use of kinematic data as a
226 complement to clinical and functional assessments. If clinicians can recognize a child's motor
227 pattern and define the characteristics of the severity of the impairment and functional deficit, this
228 will help them to target therapies using an impairment-based approach.

229 The kinematic deviations which differed the most between the children with uCP and the TDC
230 were elbow supination and wrist extension (mean deviation difference of 12-16° between groups).
231 The extent of the uCP deviations was more than double (APS of 20° in BE API) that found in the
232 unimanual protocol by Jaspers et al. (APS of 8°) [5,24], possibly because the additional need for

233 interlimb coordination during bimanual tasks reduces motor performance [1,28]. This further
234 supports the importance of assessing bimanual function to approach real life limitations and
235 reinforces the need to focus on elbow and wrist movements.

236 In the literature, the choice of the most appropriate task to provide an overall description of UL
237 movement remains debated [23,25]: UL movement varies considerably according to the task, as
238 was found in the present study. This suggests that protocols should include at least 5 tasks,
239 several of which should focus on elbow supination and wrist extension, to fully assess bimanual
240 function. Moreover, the clustering analysis provided new a perspective for kinematic data mining,
241 with clinical applications. Quantitative data-driven approaches can be used to provide more
242 specific information regarding movement execution and thus help to determine individualized,
243 goal-directed therapeutic interventions.

244 This study has several limitations. It was a pilot study which involved the classification of UL
245 movements by cluster analysis in a sample of 20 children with uCP. The analysis only included
246 kinematic variables, however spatiotemporal variables and variables relating to movement quality
247 (e.g. smoothness, straightness) could be added to classify the overall movement of the impaired
248 UL. Although this method identified different motor patterns, the small number of children with
249 Pattern 3 (n=3) prevented the analysis of correlations with impairment and function scores. One
250 TDC was classified as Pattern 2 while all the others were classified as Pattern 1. This likely
251 highlights a limitation of the clustering approach we used. The accuracy of the clustering was,
252 however, high since the TDC were identified as a homogenous group (except for one child), each
253 pattern was characterized by different AVS and the motor patterns corresponded to the children's
254 clinical profiles. The sex ratio differed significantly between the children with uCP and the TDC
255 and could constitute a bias in the between-group comparison.

256

257 **5. CONCLUSION**

258 Three distinct patterns of UL kinematic deviations were identified in children with uCP during
259 bimanual tasks: pronation-supination and wrist extension were the most decisive variables. The
260 results showed the contribution of each DoF to abnormal UL movement as well as the clinical
261 profiles that corresponded to each motor pattern. Cluster analysis may facilitate the identification
262 of pathological movement patterns in children with uCP, contributing to both the overall
263 understanding of UL impairments, and to the planning of goal-directed therapeutic interventions
264 for individual patients.

265

266

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DECLARATIONS OF INTEREST

Declarations of interest: none

REFERENCES

- [1] Greaves S, Imms C, Dodd K, Krumlinde-Sundholm L. Assessing bimanual performance in young children with hemiplegic cerebral palsy: a systematic review. *Developmental Medicine & Child Neurology* 2010;52:413–21. <https://doi.org/10.1111/j.1469-8749.2009.03561.x>.
- [2] Klingels K, Demeyere I, Jaspers E, De Cock P, Molenaers G, Boyd R, et al. Upper limb impairments and their impact on activity measures in children with unilateral cerebral palsy. *Eur J Paediatr Neurol* 2012;16:475–84. <https://doi.org/10.1016/j.ejpn.2011.12.008>.
- [3] Wang T-N, Howe T-H, Liang K-J, Chang T-W, Shieh J-Y, Chen H-L. Bimanual motor performance in everyday life activities of children with hemiplegic cerebral palsy. *Eur J Phys Rehabil Med* 2021. <https://doi.org/10.23736/S1973-9087.21.06504-7>.
- [4] Cacioppo M, Marin A, Rauscent H, Le Pabic E, Gaillard F, Brochard S, et al. A new child-friendly 3D bimanual protocol to assess upper limb movement in children with unilateral cerebral palsy: Development and validation. *Journal of Electromyography and Kinesiology* 2020;55:102481. <https://doi.org/10.1016/j.jelekin.2020.102481>.
- [5] Gaillard F, Cretual A, Cordillet S, Le CC, Gonthier C, Bouvier B, et al. Kinematic motion abnormalities and bimanual performance in children with unilateral cerebral palsy. *Dev Med Child Neurol* 2018;60:839–45. <https://doi.org/10.1111/dmcn.13774>.
- [6] Sarcher A, Brochard S, Hug F, Letellier G, Raison M, Perrouin-Verbe B, et al. Patterns of upper limb muscle activation in children with unilateral spastic cerebral palsy: Variability and detection of deviations. *Clinical Biomechanics* 2018;59:85–93. <https://doi.org/10.1016/j.clinbiomech.2018.09.005>.
- [7] Raouafi S, Achiche S, Begon M, Sarcher A, Raison M. Classification of upper limb disability levels of children with spastic unilateral cerebral palsy using K-means algorithm. *Med Biol Eng Comput* 2018;56:49–59. <https://doi.org/10.1007/s11517-017-1678-y>.
- [8] Tang L, Chen X, Cao S, Wu D, Zhao G, Zhang X. Assessment of Upper Limb Motor Dysfunction for Children with Cerebral Palsy Based on Muscle Synergy Analysis. *Front Hum Neurosci* 2017;11:130. <https://doi.org/10.3389/fnhum.2017.00130>.
- [9] Simon-Martinez C, Jaspers E, Maillieux L, Desloovere K, Vanrenterghem J, Ortibus E, et al. Negative Influence of Motor Impairments on Upper Limb Movement Patterns in Children with Unilateral Cerebral Palsy. A Statistical Parametric Mapping Study. *Front Hum Neurosci* 2017;11. <https://doi.org/10.3389/fnhum.2017.00482>.
- [10] Eliasson A-C, Krumlinde-Sundholm L, Rösblad B, Beckung E, Arner M, Ohrvall A-M, et al. The Manual Ability Classification System (MACS) for children with cerebral palsy: scale development and evidence of validity and reliability. *Dev Med Child Neurol* 2006;48:549–54. <https://doi.org/10.1017/S0012162206001162>.
- [11] Wu G, van der Helm FCT, Veeger HEJD, Makhsous M, Van Roy P, Anglin C, et al. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion--Part II: shoulder, elbow, wrist and hand. *J Biomech* 2005;38:981–92. <https://doi.org/10.1016/j.jbiomech.2004.05.042>.
- [12] Lempereur M, Leboeuf F, Brochard S, Rousset J, Burdin V, Rémy-Néris O. In vivo estimation of the glenohumeral joint centre by functional methods: accuracy and repeatability assessment. *J Biomech* 2010;43:370–4. <https://doi.org/10.1016/j.jbiomech.2009.09.029>.
- [13] Gamage SSHU, Lasenby J. New least squares solutions for estimating the average centre of rotation and the axis of rotation. *J Biomech* 2002;35:87–93. [https://doi.org/10.1016/s0021-9290\(01\)00160-9](https://doi.org/10.1016/s0021-9290(01)00160-9).
- [14] Jaspers E, Feys H, Bruyninckx H, Klingels K, Molenaers G, Desloovere K. The Arm Profile Score: A new summary index to assess upper limb movement pathology. *Gait & Posture* 2011;34:227–33. <https://doi.org/10.1016/j.gaitpost.2011.05.003>.
- [15] Krumlinde-Sundholm L, Holmefur M, Kottorp A, Eliasson A-C. The Assisting Hand Assessment: current evidence of validity, reliability, and responsiveness to change. *Developmental Medicine & Child Neurology* 2007;49:259–64. <https://doi.org/10.1111/j.1469-8749.2007.00259.x>.
- [16] Arnould C, Penta M, Renders A, Thonnard J-L. ABILHAND-Kids: a measure of manual ability in children with cerebral palsy. *Neurology* 2004;63:1045–52. <https://doi.org/10.1212/01.wnl.0000138423.77640.37>.
- [17] Paternostro-Sluga T, Grim-Stieger M, Posch M, Schuhfried O, Vacariu G, Mittermaier C, et al. Reliability and validity of the Medical Research Council (MRC) scale and a modified scale for

- testing muscle strength in patients with radial palsy. *J Rehabil Med* 2008;40:665–71. <https://doi.org/10.2340/16501977-0235>.
- [18] Masson E. La paralysie cérébrale de l'enfant : guide de la consultation. Examen neuro-orthopédique du tronc et des membres inférieurs, C. Bérard et al., Sauramps Médical (2008). 265 pp., 1 DVD, ISBN : 978 2 84023 550 7. EM-Consulte n.d. <https://www.em-consulte.com/article/218727/article/la-paralysie-cerebrale-de-lenfant-guide-de-la-cons> (accessed May 8, 2021).
- [19] Mutlu A, Livanelioglu A, Gunel MK. Reliability of Ashworth and Modified Ashworth scales in children with spastic cerebral palsy. *BMC Musculoskelet Disord* 2008;9:44. <https://doi.org/10.1186/1471-2474-9-44>.
- [20] Witten DM, Tibshirani R. A framework for feature selection in clustering. *J Am Stat Assoc* 2010;105:713–26. <https://doi.org/10.1198/jasa.2010.tm09415>.
- [21] Abbasi L. Kinematic cluster analysis of the crouch gait pattern in children with spastic diplegic cerebral palsy using sparse K-means method. *Clinical Biomechanics* 2021:7.
- [22] Joshi KD, Nalwade PS. Modified K-Means for Better Initial Cluster Centres n.d.:1.
- [23] Jaspers E, Desloovere K, Bruyninckx H, Klingels K, Molenaers G, Aertbeliën E, et al. Three-dimensional upper limb movement characteristics in children with hemiplegic cerebral palsy and typically developing children. *Res Dev Disabil* 2011;32:2283–94. <https://doi.org/10.1016/j.ridd.2011.07.038>.
- [24] Mailleux L, Jaspers E, Ortibus E, Simon-Martinez C, Desloovere K, Molenaers G, et al. Clinical assessment and three-dimensional movement analysis: An integrated approach for upper limb evaluation in children with unilateral cerebral palsy. *PLoS One* 2017;12. <https://doi.org/10.1371/journal.pone.0180196>.
- [25] Butler EE, Ladd AL, Louie SA, Lamont LE, Wong W, Rose J. Three-dimensional kinematics of the upper limb during a Reach and Grasp Cycle for children. *Gait Posture* 2010;32:72–7. <https://doi.org/10.1016/j.gaitpost.2010.03.011>.
- [26] Shierk A, Lake A, Haas T. Review of Therapeutic Interventions for the Upper Limb Classified by Manual Ability in Children with Cerebral Palsy. *Seminars in Plastic Surgery* 2016;30:014–23. <https://doi.org/10.1055/s-0035-1571256>.
- [27] Sakzewski L, Ziviani J, Boyd RN. Efficacy of upper limb therapies for unilateral cerebral palsy: a meta-analysis. *Pediatrics* 2014;133:e175-204. <https://doi.org/10.1542/peds.2013-0675>.
- [28] Rudisch J, Butler J, Izadi H, Zielinski IM, Aarts P, Birtles D, et al. Kinematic parameters of hand movement during a disparate bimanual movement task in children with unilateral Cerebral Palsy. *Hum Mov Sci* 2016;46:239–50. <https://doi.org/10.1016/j.humov.2016.01.010>.

Figure 1: Recruitment flow chart for the children with uCP

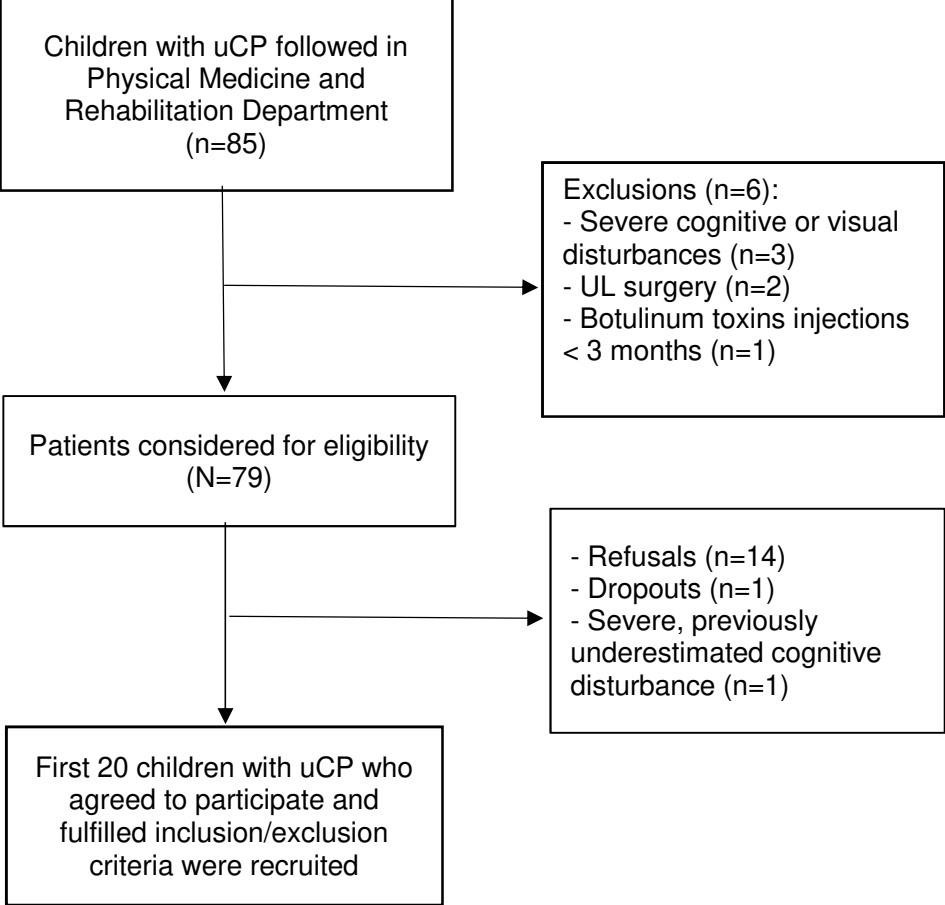


Figure 1 caption: Recruitment flow chart for the children with uCP

uCP: unilateral cerebral palsy

Figure 2: Motor patterns determined by clustering of kinematic deviations (AVS)

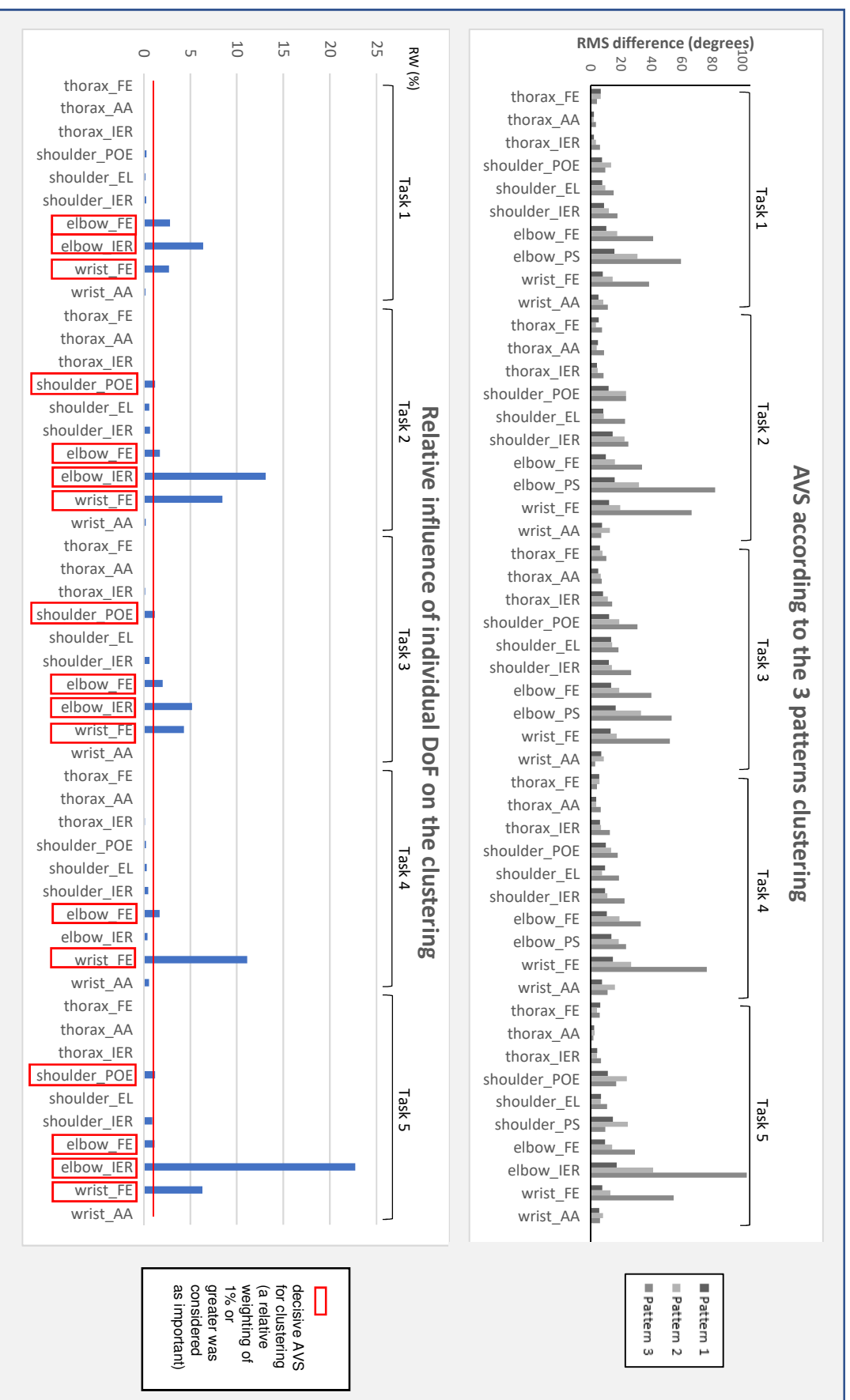


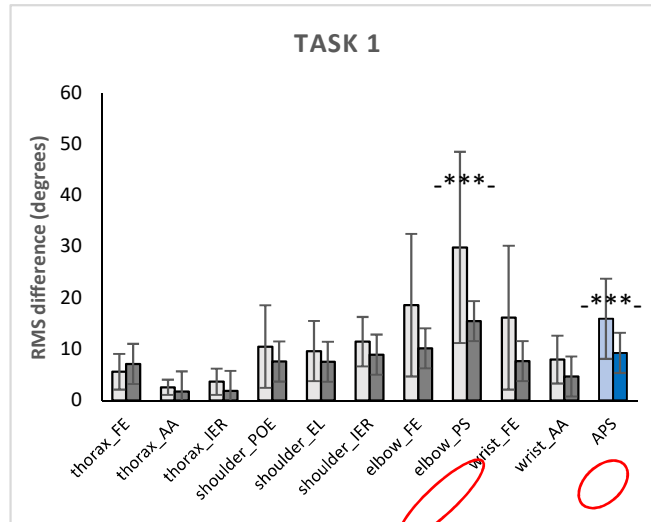
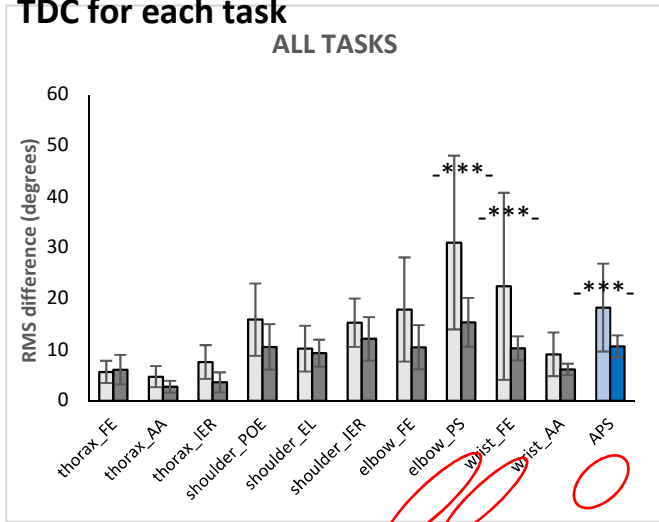
Figure 2 caption: Motor patterns determined by clustering of kinematic deviations (AVS)

Fig 2.1: Arm Variable Scores of all children according to the three patterns for the entire protocol.

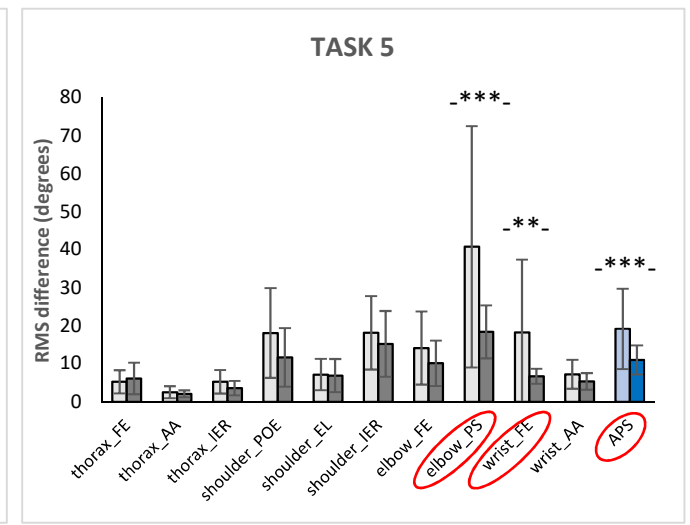
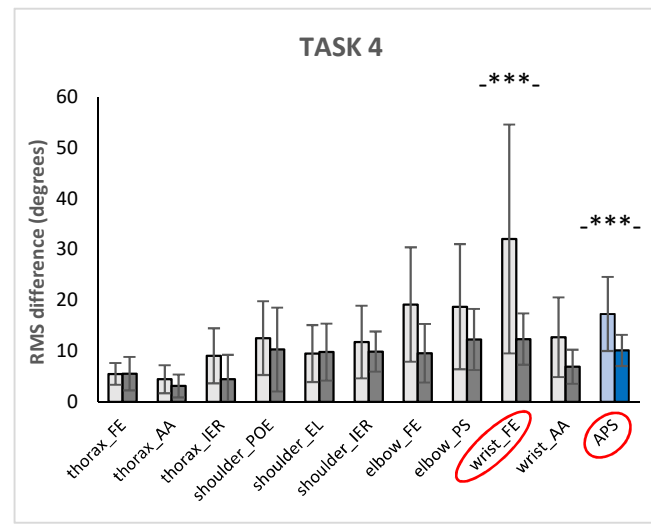
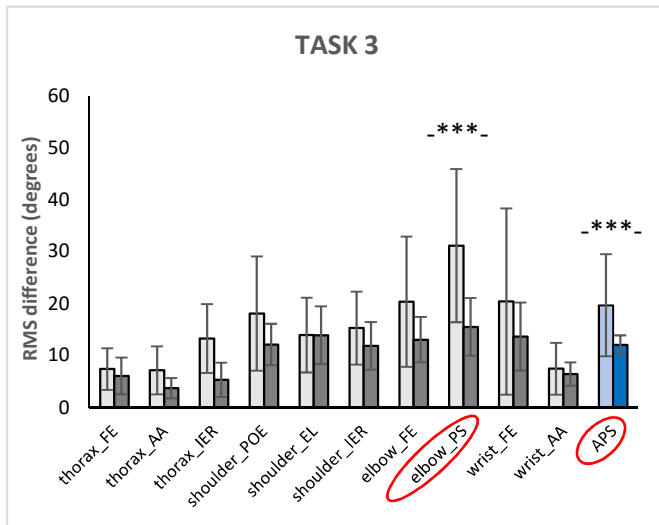
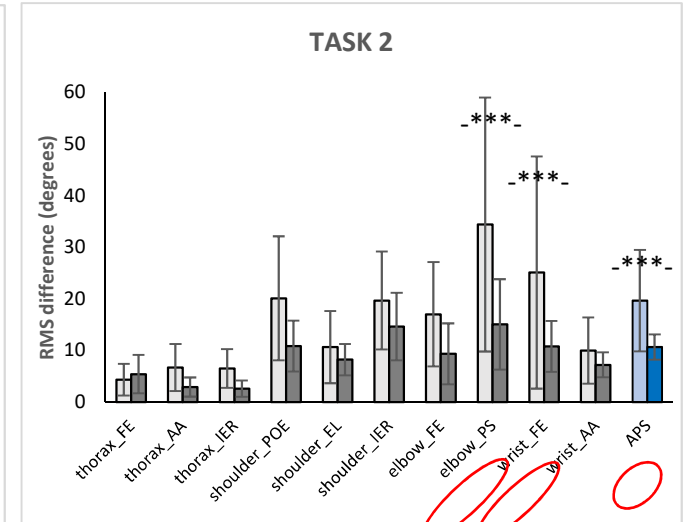
Fig 2.2: Weights of Arm Variable Scores (AVS) in the clustering expressed as the relative weighting (RW=% of total W). A threshold of 1% was chosen to establish the importance of each variable, in accordance with Abbasi et al 2021. AA: abduction-adduction; EL: elevation; FE, flexion-extension; IER: internal-external rotation; POE: plane of elevation; PS: pronation-supination.

Figure 3: Arm Movement Analysis Profile

TDC for each task



of children with uCP compared to



□ uCP children ■ TD children

Figure 3 caption: Arm Movement Analysis Profile of children with uCP compared to TDC for each task

Arm Movement Analysis Profiles (AMAP) in children with unilateral cerebral palsy (uCP) and typically developing (TD) children for the entire protocol and for each of the five BE API tasks. Each bar corresponds to one Arm Variable Score (AVS: the deviation index for a kinematic variable [joint angle]). The height represents the RMS difference across time between each joint angle of a given child with uCP and the mean value for the same joint angle of the TDC. The Arm Profile Score (APS) for the overall upper limb movement deviation is displayed on a column to the right, and is the average RMS difference across time for all kinematic variables. Significant differences between both groups are marked with ** $p < .01$; *** $p < .001$. AA: abduction-adduction; EL: elevation; FE, flexion-extension; POE: plane of elevation. PS: pronation-supination

Table 1: Description of the kinematic deviations of each task according to the 3 UL motor patterns

	AVS (RMS differences in degrees)									
	thorax_FE	thorax_AA	thorax_IER	shoulder_POE	shoulder_EL	shoulder_IER	elbow_FE	elbow_PS	wrist_FE	wrist_AA
Pattern 1 (n=28)										
Task 1	6,52	2,14	2,14	7,40	7,54	8,78	10,26	15,58	8,01	5,03
Task 2	5,18	4,72	4,16	11,78	8,34	14,45	9,91	15,80	12,02	7,38
Task 3	6,06	4,86	8,05	12,05	13,39	12,01	13,43	16,42	13,15	6,86
Task 4	5,57	3,51	6,11	9,98	9,49	9,50	10,61	13,55	14,59	7,38
Task 5	6,24	2,23	4,23	11,32	6,71	14,55	9,46	17,12	7,58	5,57
Pattern 2 (n=9)										
Task 1	6,64	1,92	3,49	13,37	9,56	11,88	17,47	30,74	14,49	8,32
Task 2	3,50	3,98	4,58	23,24	8,58	22,30	15,94	31,74	19,51	12,54
Task 3	7,68	6,56	11,31	18,74	14,09	13,99	18,71	33,12	17,05	8,53
Task 4	5,73	3,58	6,72	13,39	7,36	10,96	18,96	18,49	26,60	15,91
Task 5	4,02	2,54	4,07	23,85	6,66	24,43	14,15	41,19	13,01	8,16
Pattern 3 (n=3)										
Task 1	4,14	3,40	6,13	9,54	15,08	17,59	41,08	59,50	38,44	11,24
Task 2	7,35	8,82	8,49	23,27	22,58	24,78	33,79	81,95	66,50	6,99
Task 3	10,26	7,20	14,15	30,71	18,30	26,56	39,88	53,31	52,20	2,87
Task 4	4,09	6,51	12,57	17,83	18,55	22,34	32,96	23,26	76,48	11,14
Task 5	5,89	1,84	6,77	16,71	10,72	9,57	29,15	102,83	54,66	6,18

Arm Variable Score (AVS), the deviation index for each kinematic variable (joint angle), expressed in degrees. AVS more than 10 degrees are in bold and highlighted in grey. AA: abduction-adduction; EL: elevation; FE, flexion-extension; IER: internal-external rotation; POE: plane of elevation; PS: pronation-supination; RMS: Root Mean Square; UL: upper limb.

Table 2: Comparison between deviant movement patterns and clinical characteristics of children with uCP

	Group 1 (N=8)	Group 2 (N=9)	Group 3 (N=3)	p-value
Age (years, SD)	10.4 (2.4)	12 (3.5)	12.3 (3)	0.48
Sex, boys (N, %)	6 (40%)	6 (40%)	3 (20%)	0.56
Paretic side, right (N, %)	6 (60%)	2 (20%)	2 (20%)	0.08
MACS level (N, %)				<.001
- MACS I	7 (70%)	3 (30%)	/	
- MACS II	1 (20%)	4 (80%)	/	
- MACS III	/	2 (40%)	3 (60%)	
AHA (unit-AHA, SD)	80.3 (10.4)	64.1 (11.6)	40 (2.6)	<.001
Abilhand-Kids (% , SD)	83.6 (9.8)	68.9 (10.9)	64.7 (3.8)	0.009
Impairment assessments				
- MRC	67.4 (7.7)	55 (7.6)	40.7 (7.5)	<.001
- SMC	30.3 (1.1)	23.8 (4.1)	15.8 (3.0)	<.001
- MAS	0.3 (0.7)	1.8 (1.6)	10.3 (5.5)	<.001

Comparisons between children with unilateral Cerebral Palsy (uCP) of each pattern were performed using one-way ANOVA or Kruskal-Wallis test according to the distribution.

MACS, Manual Ability Classification System; N, number; AHA, Assisting Hand Assessment; MRC, Medical Research Council; SMC, Selective motor control; MAS, modified Ashworth scale