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Evaluation of the factors that impact upper limb coordination in children with cerebral palsy: A narrative review

Evaluación de los factores que impactan la coordinación de miembros superiores en niños con parálisis cerebral: Una revisión narrativa

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Abstract. Introduction: The purpose of this study is to assess the evolution of motor coordination deficits in upper limbs in children with cerebral palsy (CP). Methods: This is a narrative review of studies monitoring the PRISMA guidelines that were followed during the design, research, and reporting. Results: The articles were screened by reading the titles and abstracts or full articles. This process resulted in a total of 11 studies that met the selection criteria and were therefore included in the narrative review and considered eligible for quality assessment through the MINORS scale, NIH quality assessment tool for Observational Cohort and Cross-Sectional Studies and CASP checklist. Conclusion: Factors that include body structures and functions, time and age of the child, the relationship between factors, and assessment tools can influence the assessment and presentation of upper limb coordination in children with CP. High level research that focuses on interventions that address the factors found in this review are warranted.
Keywords: cerebral palsy, children, upper extremity.

Resumen. Introducción: El propósito de este estudio es evaluar la evolución de los déficits de coordinación motora en miembros superiores en niños con parálisis cerebral (PC).
Métodos: esta es una revisión narrativa de los estudios que monitorean las pautas PRISMA que se siguieron durante el diseño, la investigación y la presentación de informes. Resultados: Los artículos fueron cribados mediante la lectura de los títulos y resúmenes o artículos completos. Este proceso dio como resultado un total de 11 estudios que cumplieron con los criterios de selección y, por lo tanto, se incluyeron en la revisión narrativa y se consideraron elegibles para la evaluación de calidad a través de la escala MINORS, la herramienta de evaluación de calidad NIH para estudios transversales y de cohortes observacionales y la lista de verificación CASP. Conclusión: Los factores que incluyen las estructuras y funciones corporales, el tiempo y la edad del niño, la relación entre factores y las herramientas de evaluación pueden influir en la evaluación y presentación de la coordinación de miembros superiores en niños con parálisis cerebral. Se justifica una investigación de alto nivel que se centre en intervenciones que aborden los factores encontrados en esta revisión.
Palabras clave: parálisis cerebral, niños, extremidad superior.

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Introduction

Cerebral palsy (CP) is characterized by impaired movement coordination and muscle tone regulation due to weakness, motor control abnormalities and spasticity (Odding, Roebroeck, & Stam, 2006) Cerebral palsy can be categorized as unilateral or bilateral based on the topography of the affected limbs. The most common form of the condition is unilateral cerebral palsy (UCP), which impairs the use of one hand and consequently disrupts bimanual coordination (Reid, Rose, & Boyd, 2015). In over 80% of the CP cases, there is an upper limb disorder, mainly manifested by decreased hand control and the presence of contractures, which, in time, leads to the adoption of abnormal postures which affect the abilities of the CP patients' hands. The involved upper extremity may demonstrate abnormal muscle tone with posturing into wrist flexion, ulnar deviation, elbow flexion, and shoulder rotation. These motor, as well as sensory deficits, affect the coordination required during reaching and grasping. The impaired manual function is one of the significant causes of activity limitations for individuals with CP (Jami Vargas, Caisapanta Acaro, Zambrano Pintado, & Bonilla Jurado, 2021). Independent performance of everyday activities is strongly related to hand function and manual ability. Many activities of daily living (ADL) require the coordinated use of both hands. The inability to effectively coordinate the upper limbs impacts functional independence and quality of life (Radziejowski et al., 2022). The degree of disability and coordination deficits will in part depend on the specific contractures, reduced strength, as well as tactile and proprioceptive disturbances, which may further impact fine motor skills and upper limb motor coordination (Charles & Gordon, 2006). Patterns and use of upper limb motor involvement in CP depend also upon the patient's age (Gameel & Tartour, 1974). The most rapid development occurs before 4 years of age with a decrease in the development of hand use during bimanual activities after 9 years of age. Children with unilateral CP maintain their attained level of hand use until the age of 13 years. It may be important to use an upper limb coordination approach with older-aged children with CP to maintain or further enhance performance (Klingels et al., 2018).

Coordination disorders have a strong negative influence on the functional independence level in children with

CP. Deficits in bimanual coordination are common due to motor control abnormalities that impact functional independence and quality of life (Sidiropoulos, Santamaria, & Gordon, 2021). Traditionally, the upper limb motor coordination deficits treatment approach has focused on the effects of spasticity on upper limb function (Boyd, Morris, & Graham, 2001; Damiano, Quinlivan, Owen, Shaffrey, & Abel, 2001). Further investigation has demonstrated that muscle weakness and sensory functions should be prioritized over spasticity (Russo, Skuza, Sandelance, & Flett, 2019) Although its impact on activity, participation, motor coordination, upper limb function, and independence in daily activities remains unclear, improving muscle strength seems to be a key component in the therapeutic approach to improve the affected upper limb and consequently bimanual coordination (Mailleux & Feys, 2019).

Children with CP also present stability deficiencies due to the impaired neuromuscular system, biomechanical limitations previously described, and/or experience deficits or inability to effectively coordinate their limbs due to the lack of previous experience in the reproduction of certain movements (Sidiropoulos et al., 2021). A different and efficacious approach has been described in the literature to improve bimanual coordination in CP using motor learning concepts such as Constraint-Induced Movement Therapy (CIMT) (Charles, Lavinder, & Gordon, 2001) and Bimanual Training (Charles & Gordon, 2006) to improve bimanual spatiotemporal coordination during the performance of a discrete task. A recent study (Sidiropoulos et al., 2021) reported improvements in coordination and stability in children with CP after receiving continuous inter-limb coordination between the arms and between the more-affected arm and leg, evaluated using relative phase analysis during four gross motor tasks. Increased gross motor practice during upper extremity interventions should be taken into consideration in the therapeutic approach to the upper limb in children with CP.

Regarding tactile and somatosensory-motor intervention, upper limb somatosensory stimulation seems promising for improvements in motor planning and bimanual coordination in children with CP (Auld & Johnston, 2018). Approximately 40% of children with CP cannot detect touch through their hands at all (have an impairment in both tactile registration and perception), and an additional 37% cannot understand or interpret what stimuli touched their hands (Auld, Boyd, Moseley, Ware, & Johnston, 2012). These tactile deficits contribute to restricted outcomes in motor function in both unimanual capacity and bimanual performance due to deficits in spatial tactile perception. There is a lack of interventions examined in the literature directed specifically at improving tactile dysfunction in children with CP. However, motor performance and coordination could also be affected in children with CP due to tactile deficits (Auld, Russo, Moseley, & Johnston, 2014).

The evaluation and approach to manage the deficits in motor coordination in children with CP has been evolving in the last decade. Nowadays, constraint-induced movement therapy (mCIMT) and bimanual intensive therapy (BIM) represent the two most spreaded contemporary approaches in upper limb rehabilitation in children with unilateral CP (Reid et al., 2015). Assuming the key role of coordination disorders in rehabilitative pathway, the purpose of this study is to assess the evolution of motor coordination deficits in the upper limbs of children with cerebral palsy in order to enrich the knowledge of its specific assessment and management.

Methods

Search strategy

The literature search was conducted independently by two authors (S.D. and A.B.) on MEDLINE, for articles published before January 1, 2022, using the keywords: "Cerebral palsy, children, upper extremity, coordination, psychomotor performance, rehabilitation, assessment", combined with Boolean operators, MeSH terms and completing the searching operation with manual research by a search methodology expert. The search strategy was restricted to English-language publications and human research.

Population, Intervention, Control, and Outcomes

The selected studies' participants had to be male or female children with a diagnosis of cerebral palsy. The psychomotor function of the upper limb was then assessed in the included studies. The selected outcome was upper limb coordination.

Studies selection

After the independent titles and abstracts screening of the identified studies by two authors (A.B. and A.B.), full texts of the potentially relevant articles were retrieved. All disagreements between the reviewers were settled with another author (J.H.V.). The manual search of relevant studies' references was applied to retrieve additional articles. Exclusion criteria were editorials, commentaries, review articles, case reports, meta-analyses and letters, and studies that included adult subjects, diplegic participants and those who had undergone treatment interventions previously.

Quality assessment

The quality assessment of the cross-sectional and cohort studies included in the present study has been conducted using the NIH quality assessment tool for Observational Cohort and Cross-Sectional Studies (NIH OC&CS) [https://www.nhlbi.nih.gov/health-topics/study-quality-assessment-tools], a 14-question form designed to focus on the key concepts for evaluating the internal validity of a study. The quality assessment of included case-control studies was using standardized criteria based on the Critical Appraisal Skills Programme (CASP) tool, an 11-question checklist. The Methodological index for non-

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randomized studies (MINORS) has been used to assess methodological quality and risk of bias in the follow-up studies. The tool is comprised of 12 items and each item is scored from 0 to 2.

Results

Study selection

Eleven studies met the inclusion criteria (Chaleat-Valayer et al., 2015; Hadzagic Catibusic, Uzicanin, Bulja, & Gasal Gvozdenovic, 2019; Klevberg, Jahnsen, Elkjaer, & Zucknick, 2021; Klingels et al., 2012; Klingels et al., 2018; Kuczynski, Kirton, Semrau, & Dukelow, 2021; Makki, Duodu, & Nixon, 2014; Nordstrand, Eliasson, & Holmefur, 2016; Russo et al., 2019; Tang et al., 2017; Tonmukayakul et al., 2020), (Figure 1). A total of 286 patients with the diagnosis of cerebral palsy were included in the studies. The primary characteristics of the included studies are summarized in Table 1. Three studies were case studies (Nordstrand et al., 2016; Tang et al., 2017; Tonmukayakul et al., 2020) whom proposed a different assessment protocols for children with CP, eight studies were observational studies, in particular four were cohort studies (Klevberg et al., 2021; Klingels et al., 2012; Klingels et al., 2018; Kuczynski et al., 2021), and four were cross-sectional studies (Chaleat-Valayer et al., 2015; Klevberg et al., 2021; Makki et al., 2014; Russo et al., 2019). The five included studies were conducted in Europe (3) and the United States of America (US) (2) and were published between the years 2012 to 2021.

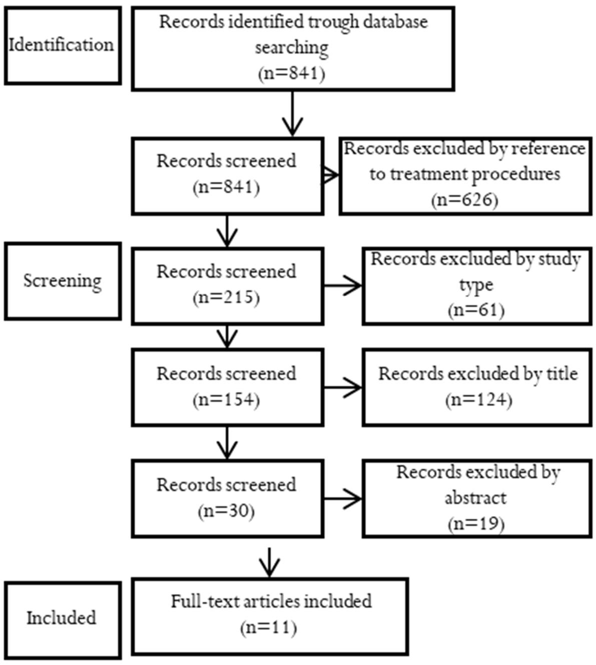

Figure 1

Risk of bias within and across the studies

All the MINORS scores used to assess the follow-up studies, as well as the NIH quality assessment tool for Observational Cohort and Cross-Sectional Studies scores, are reported in Table 1. Only the study of Tang et. Al., (Tang et al., 2017) was assessed using The CASP tool obtaining a score of 7/14.

Study Findings

1) In the cohort study by Klingels et al.,(Klingels et al., 2018) they presented the results of a temporal follow-up study of 5 years duration on the upper limb function of 81 children with unilateral cerebral palsy whose average age at the first evaluation was 9 years and 11 months. Subjects included (43 boys and 38 girls) with congenital (N =69, 85%) or acquired (N =12, 15%) brain lesions. The authors studied factors influencing body function and the International Classification of Functioning, Disability, and Health activity level. The results showed increased limitations in passive range of motion mainly in children older than 9 years of age onwards. In addition, grip strength and unimanual ability improved over time, especially in children who were mildly affected. In contrast, the spontaneous use of the affected upper limb in bimanual activities became less effective in children older than 9 years of age. Results at the level of body function showed more limitations of passive range of motion over time, developing mainly in children aged 9 years and older, while this process stabilized around 14-15 years of age. Visual inspection showed more pronounced limitations in wrist extension. The primary outcome considered in this study was the level of body function, for which a standardized testing protocol was performed including upper extremity passive range of motion, muscle tone, muscle strength and grip strength. Passive range of motion of shoulder flexion, abduction, external and internal rotation, elbow extension, forearm supination and wrist extension was measured with a goniometer. The quality score of the study was 10/16 MINORS score.

2) Russo et al.,(Russo et al., 2019) performed a cross-sectional study to examine the relationship between upper limb impairments and independence in self-care in 108 children with unilateral cerebral palsy (46 females, 62 males; mean age 8 years 7 months). They assessed upper extremity muscular strength, spasticity, sensation, motor control and processing skills, as well as independence in self-care as a functional outcome using structural equation modeling. The main conclusion of the study was that manual ability (muscle power and motor control) and processing skills are the variables most strongly related to better functional outcomes as defined by independence in self-care in children with unilateral cerebral palsy. The results of the analysis indicated that muscle power and its key relationship to manual ability was a more critical element to address in order to improve independence in self-care than spasticity in children with unilateral cerebral palsy. The quality score of the study was 10/14 NIH OC&CS score.

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Table 1.
Characteristics of Included Studies.

Author, yrs	Aim of the study	Study design	Participants	Outcome measures	Reported results	Methodological Quality score
Klingels et al. (2018)	To report the five-year evolution in upper limb function and identify factors influencing time trends.	Cohort study of 5 years Follow up study	Eighty-one children (mean age 9 y and 11 mo, SD 3 y and 3 mo) were assessed	Passive range of motion (PROM), tone, muscle, and grip strength were assessed. Activity measurements included Melbourne Assessment, Jebsen-Taylor test, Assisting Hand Assessment (AHA), and ABILHAND-Kids.	Results: At 5-year follow-up, PROM ($p < 0.001$) and AHA scores ($p < 0.001$) decreased, whereas an improvement was seen for grip strength ($p < 0.001$), Melbourne Assessment ($p = 0.003$), Jebsen-Taylor test ($p < 0.001$), and ABILHAND-Kids ($p < 0.001$). Age influenced the evolution of AHA scores ($p = 0.003$), with younger children being stable over time, but from 9 years onward, children experienced a decrease in bimanual performance. Manual Ability Classification System (MACS) levels also affected the evolution of AHA scores ($p = 0.02$), with stable scores in MACS I and deterioration in MACS II and III. In conclusion, over 5 years, children with unilateral CP develop more limitations in PROM, and although capacity measures improve, the spontaneous use of the impaired limb in bimanual tasks becomes less effective after the age of 9 years.	MINORS 10/16
Russo et al. (2019)	To examine the relationships between upper limb impairments and independence in self-care (ISC) in children with unilateral cerebral palsy (CP).	Case-control	One hundred and eight children with unilateral CP (46 females, 62 males; mean age 8y 7mo, SD 3y 9mo) recruited from a population register were assessed	Upper limb muscle power, spasticity, sensation, motor control, and process skills, and for ISC as the functional outcome using structural equation modelling	The results of this analysis show that children with unilateral CP, while expected to perform at peer levels, have significant impairments that affect their ISC. This study demonstrates that, to improve ISC for children with unilateral CP, the modalities of muscle power and sensory function should be prioritized over spasticity and must be managed effectively in the context of the child's age and cognitive abilities.	NIH OC&CS 14/24
Kuczynski et al (2021)	To assess the relationship between position sense and reaching with the hemiparetic upper limb in children with perinatal stroke.	Cohort study	Children and adolescents with perinatal stroke were recruited from a population-based research cohort (Alberta Perinatal Stroke Project) and included in the present study if they met the following criteria: 1.Age 6–19 years, and born at term > 36 weeks gestational age	Arm position-matching (three parameters: variability [Varxy], contraction/expansion [Areaxy], systematic spatial shift [Shiftxy]) and visually guided reaching (five parameters: posture speed [PS], reaction time [RT], initial direction error [IDE], speed maxima count [SMC], movement time [MT]). Additional clinical assessments of sensory (thumb localization test) and motor impairment (Assisting Hand Assessment, Chedoke-McMaster Stroke Assessment) were completed and compared to robotic measures.	Position-matching performance in children with stroke did not correlate with performance on the visually guided reaching task. Robotic sensory and motor measures correlated with only some clinical tests	NIH OC&CS 8/14
Makki et al. (2014)	To determine the prevalence and pattern of upper limb involvement in children with cerebral palsy (CP), how this relates to function and how well these problems are recognised and treated.	Cross-sectional study	One hundred consecutive patients were recruited at a specialist children's hospital, a regional centre for CP.	Gross Motor Functional Classification System (GMFCS), the Manual Ability Classification System (MACS) and the ABILHAND-Kids system, and correlated to age and pattern of upper limb involvement. Patients were examined for contractures	Results: Different patterns of upper limb involvement exist in CP, and some have a significant impact on function and cause cosmetic concerns that should not be underestimated, particularly in older children.	NIH OC&CS 8/14

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				in the shoulder, elbow, wrist and hand. Concerns about the appearance of the hand were also assessed in older children.		
Klevberg et al. (2021)	To describe the development of hand use during bimanual activities among children with unilateral cerebral palsy (CP).	Cohort study	166 children (79 females, 87 males; age range 18mo–13y	Developmental limits and rates were estimated by non-linear mixed effects models and compared between a stable limit model (SLM) and a peak and decline model. Development was described according to Manual Ability Classification System (MACS) levels and AHA performance at 18 months of age (AHA-18).	Children in MACS level I, or in the high AHA-18 group, reached highest limits and had the most rapid development (p<0.001). The developmental trajectories were different between MACS levels I, II, and III and between the high, moderate, and low AHA-18 groups. Seventy-five per cent of the children reached 90% of their estimated limit at 5 years 10 months or earlier. The SLM showed the best model fit (Akaike information criterion: 4008.99).	NIH OC&CS 10/14
Tang et al. (2017)	To explore an objective and effective method to assess the upper limb motor dysfunction of cerebral palsy (CP) children from the aspect of muscle synergy analysis	Case study	Twenty-four subjects, including 10 typically developed children (TD group, three males and seven females, 8.9 ± 2.7 years) and 14 children with CP (CP group, nine males and five females, 8.2 ± 2.6 years), were involved in this study.	Three tasks which could comprehensively reflect the extension/flexion of elbow and the adduction/abduction of shoulder joints, were designed to assess the upper limb motor dysfunction from the aspect of gross motor.	Muscle synergy analysis has great potential in the assessment of motor dysfunction	CASP 7/11
Tonmukayakul et al (2020)	To: (1) investigate the relationship between upper-limb impairment and health-related quality of life (HRQoL) for children with cerebral palsy and (2) develop a mapping algorithm from the Cerebral Palsy Quality of Life Questionnaire for Children (CPQoL-Child) onto the Child Health Utility 9D (CHU9D) measure.	Case study	76 children (40 females, 36 males) aged 6 to 15 years (mean age 9 years 7 months [SD 3y]) were assessed	Five statistical techniques were developed and tested, which predicted the CHU9D scores from the CPQoL-Child total/domain scores, age, and sex.	Most participants had mild impairments. The Manual Ability Classification System (MACS) level was significantly negatively correlated with CHU9D and CPQoL-Child (r=−0.388 and r=−0.464 respectively). There was a negative correlation between the Neurological Hand Deformity Classification (NHDC) and CPQoL-Child (r=−0.476, p<0.05). The generalized linear model with participation, pain domain, and age had the highest predictive accuracy.	NIH OC&CS 8/14
Hadžagić Ćatibušić, et al. (2018)	To assess hand function and explore the relationship between hand function and neuroimaging findings in children with unilateral spastic cerebral palsy (US CP).	Cross-sectional study	114 children with UCP (77 boys and 37 girls) 56 were with right-sided and 58 with left-sided involvement	Manual Ability Classification System (MACS, I-V)	Mild hand dysfunction in children with UCP has been significantly associated with PV WM lesions. The type of brain lesion may help to identify its timing and predict the level of hand dysfunction.	NIH OC&CS 8/14
Klingels et al.(2012)	To map the evolution of scores on upper limb measures over one year in children with unilateral CP and to identify factors that influence time trends	Cohort study of One-year follow-up study	Eighty-one children (43 males, 38 females; mean age 9y11mo (SD 3y3mo) range 5–15 y) were tested at baseline, at 6 and 12 months	Activity measurements included the Melbourne Assessment, the Jebsen–Taylor test, the Assisting Hand Assessment and the Abilhand-Kids questionnaire. Age, gender, etiology (congenital or acquired lesions) and Manual Ability Classification System (MACS) levels were analyzed as pre-	Scores for grip strength (p = 0.001) and manual dexterity (Jebsen–Taylor test, p < 0.0001) increased significantly over time. MACS level (p = 0.03) and etiology (p = 0.02) had a significant influence on the time evolution of the Jebsen–Taylor scores. Other assessments showed no significant changes.	MINORS 10/16

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				dictive factors, using mixed models.		
Chaleat-Valayer et al. (2015)	Analyze the link between unimanual capacities and bimanual performance in cerebral-palsied (CP) hemiplegic children, aged between 5 and 18 years old, studying specifically the impact of synkinesis.	Cross sectional study	71 CP hemiplegic children (35 boys and 36 girls – with average age of 8 years and 6 months; MACS levels from I to III; GMFCS from I to IV)	Melbourne Test (MUUL) for unimanual capacities and Assisting Hand Assessment (AHA) for bimanual performance – with a specific scale to analyze synkinesis during Box and Block test for affected and healthy hands, collecting synkinesis type, duration and intensity.	There is a strong correlation between unimanual capacities (MUUL) and bimanual performance (AHA) (r = 0.871). Neither age nor gender contribute to bimanual performance (AHA). Multiple linear regression shows that MUUL contributes to bimanual performance variance (AHA) by 70%. Synkinesis is partly correlated to capacities (MUUL) and accounts for 10% of the variance of the gap between capacities and bimanual performance.	NIH OC&CS 10/14
Nordstrand et al (2016)	The aim of the study was to describe the development of hand function, particularly the use of the affected hand in bimanual tasks, among children with unilateral cerebral palsy aged 18 months to 12 years.	Case study	96 children with spastic unilateral CP were included. Inclusion criteria was a diagnosis of spastic unilateral CP, age 10 years or younger at recruitment, and willingness to participate in at least three data collection points over a minimum of 12 months.	Assisting Hand Assessment (AHA)	The results were based on 702 AHA sessions. The children showed a rapid development at a young age and reached 90% of their stable limit between 30 months and 8 years. The subgroups, based on the 18-month AHA and the MACS levels respectively, had distinctly different patterns of development.	NIH OC&CS 10/14

MINORS = Methodological index for non-randomized studies.
NIH OC&CS = NIH quality assessment tool for Observational Cohor and Cross-Sectional Studies.
CASP = Critical Appraisal Skills Programme tool.

3) Chaleat-Valayer et al.(Chaleat-Valayer et al., 2015) in a cross-sectional study analyzed the relationship between unimanual abilities and bimanual performance in 71 hemiplegic children with cerebral palsy (5-18 years old; 35 boys and 36 girls). They studied the impact of synkinesis using the Melbourne Test (MUUL) for unimanual abilities, and the Assistant Hand Evaluation (AHA) for bimanual abilities with a specific scale to analyze synkinesis during the performance of the Box and Block test for the affected and healthy hands, collecting synkinesis type duration and intensity. The results of the relationship between bimanual performance (AHA) and the unimanual abilities of the affected hand (MUUL) showed that there was a very high, positive correlation (r = 0.871) between the abilities of the affected hand in test situations scored by the MUUL, and the actual use of these abilities in spontaneous bimanual activities, scored by the AHA (ability-performance link). This statistical correlation reinforced clinical practice, where many therapeutic interventions aim to improve unimanual abilities to influence performance in bimanual activities. The quality score of the study was 10/14 NIH OC&CS score.

4) Hadzagic Catibusic et al.,(Hadzagic Catibusic et al., 2019) used the data of a prospective longitudinal study in a cohort cross-sectional study of children with cerebral palsy in the U.S. (children born from 1998 onwards). The subjects were prospectively followed to determine the relationship between fine motor function about the nature of the brain lesion. They assessed hand function and explored the relationship between hand function and neuroimaging findings in 114 children (77 boys and 37 girls) with unilateral cerebral palsy, 56 with right-sided and 58 with left-sided involvement. Manual abilities were assessed according to the Manual Ability Classification System (MACS) and Neuroimaging data included magnetic resonance images and computer tomography images, with which they were objectified brain lesions were divided into five groups: maldevelopment of the brain (MAL), periventricular white matter lesions (PV WM), periventricular white matter lesions periventricular white matter lesions (PV WM), cortical/subcortical lesions, and periventricular white matter lesions (PV WM). They observed a statistically significant presentation of boys with cerebral palsy, hypothesizing a greater vulnerability to hypoxia and a higher incidence of premature delivery in boys, and found that mild hand dysfunction in children with unilateral spastic cerebral palsy was significantly associated with periventricular white matter lesions, and the type of brain lesion can help identify its timing and predict the level of hand dysfunction. The quality score of the study was 8/14 NIH OC&CS score.

5) Klevberg et al.,(Klevberg et al., 2021) described the development of hand use during bimanual activities in a cohort of 166 children (79 females, 87 males; age range 18mo-13y) with unilateral cerebral palsy. They found that children classified as level I of the MACS, or in the high Assisting Hand Assessments-18 group, reached the highest limits, and had the most rapid development ($p<0.001$). In addition, developmental trajectories were different between children classified as levels I, II and III of the MACS and between AHA-18 high, moderate, and low groups, with 75% of the children reaching 90% of their estimated limit at 5 years and 10 months of age or earlier. The most rapid development occurred before the age of 4 years for

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more than half of the children, but with great variability present both between and within groups. Children classified at lower MACS levels or with better AHA performance, at 18 months of age reached performance limits and were approaching their limits at earlier ages compared to children with higher MACS levels and lower AHA-18 performance. Most children approached a stable performance threshold before age of 6 years old. Although the children in levels I and II of the MACS reached 90% of the expected cutoff at 3 and 4 years, respectively, the corresponding age was 8 years for the level of the MACS III, concluding that children with unilateral cerebral palsy maintain their limit of hand use until at least 13 years of age. The quality score of the study was 10/14 NIH OC&CS score.

6) Klingels et al.,(Klingels et al., 2012) mapped the evolution of scores on measures taken from the upper extremities of 81 children (43 males, 38 females; mean age 9 years, 11 months) with unilateral cerebral palsy over 1 year, and identified factors that influenced time trends at baseline, 6 and 12 months, using the Melbourne assessment, Jebsen-Taylor test, AHA and Abilhand-Kids questionnaire. They used measures from the International Classification of Functioning, Disability and Health, in addition to those measuring passive range of motion, muscle tone, manual muscle strength, grip strength and MAC. At the level of bodily function, grip strength increased significantly with a mean percentage difference of 16% and 17% in the affected and unaffected hands, respectively. At the activity level, movement speed measured with the Jebsen-Taylor test improved significantly over one year, decreasing by 17% and 16%, on the hemiplegic and non-hemiplegic sides, respectively. In contrast, manual muscle strength scores remained stable for one year, and they found a positive correlation between grip strength and hand width, which may also explain the age-related increase in grip strength. Their findings led them to conclude that motor deficits, movement quality and use of the impaired hand in bimanual tasks do not spontaneously improve over a year, except for an age-related change in grip strength, but they did observe an improvement in manual dexterity, suggesting that some children may learn more adaptive movement strategies. The quality score of the study was 10/16 MINORS score.

7) Kuczynski et al.,(Kuczynski et al., 2021) used robotic technology and clinical measures to assess the relationship between position sense and motor performance of the contralesional upper extremity to that affected by stroke consequences in 48 children (26 arterial, 22 venous, mean age: 12.0±4.0 years) with hemiparetic cerebral palsy confirmed by MRI secondary to perinatal ischemic stroke, compared to the non-dominant arm of 145 controls (mean age: 12.8±3.9 years), who completed two tasks on the Kinarm robot and had additional clinical assessments of sensory (thumb localization test) and motor (AHA, Chedoke-McMaster Stroke Assessment) impairments completed and compared to robotic measures. On average, children with perinatal stroke were impaired on several position matching and visually guided reaching outcomes relative to the control group, with 17 children passing both robotic tasks, 15 passed position-matching but failed visually guided reaching, Seven subjects the failed position-matching but passed robotic reaching, and 9 failed both robotic tasks. The researchers state that robotic technology can quantify complex and discrete aspects of upper limb sensory and motor function in hemiparetic children, measuring deficits in joint position sense. Reaching with the contralateral limbs seems relatively independent of each other and presented with modest correlations. Their results indicate that behavioral impairments in position sense and visually guided reaching, as assessed with the Kinarm robot, may be independent, suggesting that sensory impairments may occur independently of motor impairments and vice versa. These findings have significance from the point of view of the importance of understanding the sensory and motor function and how they are related, as motor impairment is often the most prominent clinical impairment observed during observations of individuals with hemiparetic cerebral palsy. The quality score of the study was 8/14 NIH OC&CS score.

8) Makki et al.,(Makki et al., 2014) determined the prevalence and pattern of upper extremity involvement in 100 children with cerebral palsy divided into three age groups (under 6 years old, between 6 and 12 years old, and over 12 years old), how it relates to function, and the extent to which these problems are recognized and treated. For this purpose, they used the Functional Classification System Gross Motor Functional Classification System, the MACS, and the ABILHAND-Kids system, correlating these variables with age and upper extremity pattern. They found that 83 % of patients had upper limb involvement, 36 % had a demonstrable contracture and 69 % had reduced hand control, and children aged 12 years and older were more concerned about the appearance of their hands. The ABILHAND score was correlated strongly with the Functional Classification System Gross Motor Functional Classification System score and the MACS. This study highlights the extent to which cerebral palsy affects upper limb involvement (83% of our population), which is a significant proportion is merely a reduction in speed or object handling (MACS score of 2); however, in the study population, about half (54%) had a MACS score of 3 or higher and about a third had a demonstrable contracture. The quality score of the study was 8/14 NIH OC&CS score.

9) Nordstrand et al.,(Nordstrand et al., 2016) described by AHA and MACS assessment at regular intervals from 18 months to 12 years of age the development of affected hand use in bimanual tasks in 96 children with unilateral cerebral palsy (53 males, 43 females) aged 18 months to 12 years, and found that children with unilateral cerebral palsy increased their ability

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to use the affected hand in bimanual activities over time, but to different extents. Children with higher baseline ability had both a higher rate and developmental cutoff than children with lower baseline ability. By dividing the children into four functional groups based on their AHA at 18 months of age, the different groups reached 90 % of their stable limit between the ages of 30 months and 8 years of age. When grouped according to MACS, significantly different cut-offs were also observed. The 96 children were assessed with the AHA on 702 occasions in the age range 18 months to 12 years. The children have tested an average of seven times over 6 years, with a total of 92 children improving their performance more than the smallest detectable change (range 5-39 AHA units) during the study period. The remaining four children increased their AHA performance below the smallest detectable change. However, they were followed for a rather short period (median 24 months), two of them were included at an early age (28 and 32 months), and the other two were included at a later age (106 and 127 months). The quality score of the study was 10/14 NIH OC&CS score

10) Tang al.,(Tang et al., 2017) explored an objective and effective method to assess upper limb motor dysfunction from the aspect of muscle synergy analysis of 14 children with cerebral palsy (3 males and 7 females, 8.9 ± 2.7 years) and 10 typically developing children (9 males and 5 females, 8.2 ± 2.6 years), who performed three similar upper limb movement tasks related to elbow and shoulder joint movements, and surface electromyographic signals were recorded from 10 upper arm and shoulder muscles involved in the defined tasks. Based on the muscle synergy analysis of three upper extremity movement tasks in the typically developing group and the cerebral palsy group, the main contribution of the authors was to propose a method of a quantitative assessment of upper extremity motor dysfunction in children with cerebral palsy, finding high structure similarities among the three similar tasks (rW-3 = 0.92), however, the activation patterns were different (rC-3 = -0.08). The results of the research verified that muscle synergy analysis has great potential in the assessment of motor dysfunction. The quality score of the study was a 7/11 CASP score.

11) Tonmukayakul et al.,(Tonmukayakul et al., 2020) investigated the relationship between upper limb impairment and health-related quality of life in 76 children (40 females, 36 males) aged 6 to 15 years (mean age 9 years, 7 months) who developed a Cerebral Palsy Quality of Life Questionnaire for Children (CPQoL-Child) mapping algorithm on the Child Health Utility 9D (CHU9D) measure, evaluating the relationship between ratings of gross motor and upper limb functionality and proxy appearing on the CPQoL-Child and CHU9D, and developing a mapping algorithm that can be used to predict CHU9D utility values from the CPQoL-Child score. They found that MACS was significantly negatively correlated with CHU9D and CPQoL-Child (r-0.388 and r-0.464, respectively), in addition to a negative correlation between Neurological Hand Classification (NHDC) and CPOoL-Child (r-0.476, p<0.05), concluding that the generalized linear model with impairment, pain domain and age had the highest predictive accuracy. The quality score of the study was 8/14 NIH OC&CS score.

Discussion

The purpose of this study was to determine the evolution of motor coordination deficits in the upper limbs of children with cerebral palsy in case, cohort, and cross-sectional studies. These types of studies explored the relationship between hand function and other factors in children with CP. Several elements were presented in these studies that can help define the factors that determine the functional outcomes of children with CP. These elements include body structures and functions, time and age of the child, the relationships between factors, and assessment tools.

Body structures and function factors reported by the authors include restriction of the passive range of motion of the upper extremity (predominantly the loss of wrist extension) after nine years of age, lesions of the periventricular white matter of the brain mild have been associated with hand dysfunction in children with CP, and the highest percentage of children with CP have upper limb involvement (Cabrera, Jiménez, Adelantado, & López, 2019; Rijo, Cabrera, Moreno, Álvarez, & Lara, 2020). There are several interventions including casting, constraint-induced movement therapy, fitness training, home program instruction, and occupational therapy following botulinum toxin that have a high level of evidence to address the body structure and function limitations of children with CP (Novak et al., 2013; Ryan, Cassidy, Noorduyn, & O'Connell, 2017). Also, it was determined that muscle power and its key relationship to manual ability is a more critical element to address than spasticity to improve independence in self-care (Henríquez et al., 2021; Peña-Gónzalez, Mancha-Triguero, Moya-Ramón, & Gamonales, 2021). A recent systematic review found that children with CP that participate in a strength training program have positive functional and activity effects on muscle strength, balance, gait speed, and/or gross motor function without increasing spasticity (Merino-Andres, Garcia de Mateos-Lopez, Damiano, & Sanchez-Sierra, 2022).

Time or age is another element that was addressed in these studies. It was determined that the most rapid development of hand use occurs before 4 years of age. Unfortunately, there is limited evidence for early motor intervention for children with CP, but there is some promising evidence that early intervention incorporating child-initiated movement (based on motor-learning principles and task specificity), parental education, and environment modification can have an affirmative effect on motor development (Morgan et al., 2016). It has been suggested that intensive treatment focused on hand function should be implemented for children with CP that have severe hand impairment (Fedrizzi, Pagliano, Andreucci, & Oleari, 2003). The studies also found there are improvements in strength and manual ability over time and movement speed and manual dexterity can improve approximately 16% over one year. As children with unilateral CP age, their ability to use the affected hand in bimanual activities improves. It has been reported that hand-arm bimanual intensive therapy appears to have a positive impact on hand function in children with hemiparetic CP (El Wahab & Hamed, 2015; Villafane, 2022). Finally, children that are 12 years of age are concerned about the appearance of their hands. Positive coping mechanisms can be taught to the child and family members to improve self-esteem. These coping mechanisms can include humor, self-acceptance, seeking external support, educating others, support programs, and religion to enhance the self-esteem of a child with a hand deformity (Franzblau et al., 2015).

The relationship between factors found a strong positive relationship between bimanual performance and the unimanual abilities of the affected hand and sensory impairments may occur independently of motor impairments (Burbano Pantoja, Cárdenas Remolina, & Valdivieso Miranda, 2021; Villafane, Cantero-Tellez, & Berjano, 2019). It has been suggested that a child with CP may have a greater disability in ADL function than a standardized test might suggest (Gordon & Duff, 1999). Sensory impairments might compromise spontaneous hand use due to limited sensory input from the affected hand of the child with CP which may lead to the poor internal representation of the physical properties of objects which can result in a reduced ability to manipulate objects (Fedrizzi et al., 2003). A scoping review of the effects of sensory-based interventions with children with CP reported that sensory activities might include tactile perception, proprioceptive perception, vestibular perception, postural and ocular control and bilateral integration, and praxis (Kantor et al., 2022). The review reported that sensory-based interventions may be useful for movement development but there is only scarce and low-quality evidence comparing the interventions (Kantor et al., 2022).

Regarding the assessment of children with CP it was found that muscle synergy analysis has a great potential in the assessment of motor dysfunction and that robotic technology may be used to quantify complex and discrete aspects of upper limb sensory and motor function (Gamonales, Jiménez-Solis, Gámez-Calvo, Sánchez-Ureña, & Muñoz-Jiménez, 2022). Consistent with the shift of focus on impairments of children with CP, new outcome measures have been developed to focus on function and ability (Debuse & Brace, 2011). The systematic review reported that many outcome measures require further research to fully establish their psychometric properties but the Gross Motor Function Measure versions 88 and 66 and the Pediatric Evaluation of Disability Inventory are appropriate to determine the functional status of children with CP (Debuse & Brace, 2011). This systematic review found The Manual Ability Classification System and Neurological Hand Deformity Classification were the best predictors of health-related quality of life measures.

Conclusion

Factors that include body structures and functions, time and age of the child, the relationship between factors, and assessment tools can influence the assessment and presentation of upper limb coordination in children with CP. Future investigations should involve high-level researches that extend the assessment to different sites over the upper limbs, reviewing other motor and sensory aspects of children with CP and comparing the multidisciplinary approach as well as rehabilitation programmes evolution through time.

Limitations

Because this review focused on the influence of factors on hand function in children with CP, the strength of the level of evidence of the articles in this review is weak. Additionally, three types of studies were included in this review which limits the ability to compare the findings of the studies. High-level research that focuses on interventions that address the factors found in this review are warranted.

Conflicts of interest

The authors report no conflicts of interest. This study was supported and funded by the Italian Ministry of Health - Ricerca Corrente 2023. The authors alone are responsible for the content and writing of the paper.

Authors'contributions

Andrea Battagliano and Jorge Hugo Villafañe contributed to the study design and research project supervision; Sara Di Benedetto, Eleuterio A. Sánchez-Romero and Andrea Battagliano, have given substantial contributions to data managing, results analysis, and manuscript draft; Raquel Cantero-Tellez, Sánchez-Romero, and Kristin Valdes contributed to part supervision, and the manuscript review. All authors read and approved the final version of the manuscript.

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