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Robot-assisted therapy for upper limb impairments in cerebral palsy

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Review Article

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Robot-assisted therapy for upper limb impairments in cerebral palsy: A scoping review and suggestions for future research

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Abstract: A growing number of studies investigate the use of robotics therapy for motor (re)habilitation with children with cerebral palsy (CP). Most of these studies use functional robots in very repetitive sessions. While the therapy is effective, very few studies employ social robots, which appears to be a missed opportunity to design more compelling and enjoyable sessions for the children. In this article, we will review robot-assisted upper limb motor (re)habilitation for children with CP. Previous reviews of robot-assisted therapy for CP had mostly focused on lower limbs, or the review was made from a medical point of view, with the sole concern being the therapy's effectiveness. Here, we focus our review on robot-assisted upper limb (re)habilitation and address human–robot interaction considerations. We searched PubMed, Scopus, and IEEE databases and argue that although this area of research is promising and already effective, it would benefit from the inclusion of social robots for a more engaging and enjoyable experience. We suggest four scenarios that could be developed in this direction. The goal of this article is to highlight the relevance of the past work and encourage the development of new ideas where therapy will socially engage and motivate children.

Keywords: cerebral palsy, upper limb impairments, therapeutic robotics, motor rehabilitation

1 Introduction

The word *palsy* comes from Greek, either from paralysis (Greek: *Παράλυση*), which means "weakness and total or partial necrosis of the nerves of the extremities" or from paresis (Greek: *Πάρεση*) denoting weakness [1]. Cerebral palsy (CP) is a progressive disorder that has been well discussed throughout history. The oldest known example would be Pharaoh Siptah who ruled for 6 years in the 19th dynasty (1196–1190 BC). The first mention of CP appeared in *Corpus Hippocraticum* by Hippocrates in the fifth century BC [1]. Emperor Tiberius Claudius Nero (10 BC–54 AD) would be another famous case of CP [2]. The extensive study of CP started in the nineteenth century with William John Little who provided the first clinical description of the condition. Other significant contributions by William Osler and Sigmund Freud paved the way to the clinical definition of CP as we know it today [1].

CP is the most common movement disorder in children with a prevalence ranging between 1 and 4 per 1,000 live births across the world [3]. According to the CDC in the United States, 1 in 345 children has been diagnosed with CP [4]. In Canada, it affects 2 to 3 per 1,000 children [5], and in the United Kingdom, 1 in 400 children [6]. CP describes a group of motor impairments that mostly affect balance, movement, and muscle tone. CP is associated with lesions in areas of the brain that manage movement control, balance, and posture. CP occurs when that part of the brain does not develop as it should, or when it is damaged. CP can be congenital (antepartum), acquired during birth (intrapartum), or acquired postnatally (postpartum).

There are four main types of CP:

- **Spastic CP** represents about 80% of the cases of CP and is characterized by spasticity or high muscle tone, evidenced by jerky and stiff movements. Lesions in the motor cortex are responsible for spastic CP and affect planning and completions of voluntary movements [7]. Spastic CP can also take several forms: spastic hemiplegia (one side of the body is affected, especially the

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upper limbs and notably the hand due to unilateral lesions to the brain that can occur at birth but also later in life following a head injury. Most hemiplegia cases are caused by a perinatal stroke acquired in utero [8]), spastic diplegia (affects the lower limbs), spastic quadriplegia (affects the four limbs), and spastic monoplegia (only one limb or area of the body is affected).

- **Dyskinetic CP** is characterized by hypotonia and hypertonia. Dyskinetic CP affects the extrapyramidal system, which is responsible for involuntary movements and can be divided into dystonia (slow, strong contractions in part of or all the body) and choreoathetosis (involuntary movements). In dyskinetic CP, lesions to the basal ganglia (involved in voluntary motor movements, procedural learning, habit learning, conditional learning, eye movements, cognition, and emotion) and substantia nigra (structure involved with the reward system and movement) occur during brain development due to bilirubin encephalopathy and hypoxic–ischemic brain injury [9].
- **Ataxic CP** represents 5–10% of the cases of CP and is characterized not only mainly by coordination impairments but also by a decrease in muscle tone and display of tremors during manual precise movements. In the case of ataxic CP, lesions to the cerebellum (responsible for movement coordination and balance) are present as well [10].
- **Mixed CP** displays the symptoms of spastic, dyskinetic, and ataxic CP simultaneously to varying degrees.

Clinical symptoms of CP vary over a broad spectrum as muscle control impairments range from mild to severe, *e.g.*, some children also have speech impairments and others can have intellectual disabilities. Along with the motor impairments, the children can also present some comorbidities [11,12] such as epilepsy, dysarthria, learning difficulties, behavioural disorders, sensory impairments, sleep disorders, mental health disorders, gastro-intestinal disorders, and others.

Manual control and coordination are also critical issues for children with CP as they dramatically decrease autonomy and quality of life. Hand skills are impaired in up to 60% of children with CP [13]. Dexterous movements involving movements or force production of individual fingers are particularly impaired for children with CP. In the case of hemiplegia, the non-paretic (non-paralysed) hand may also be affected. Consequently, usual hand function rehabilitation include bimanual training and constraint-induced movement therapy [14].

Sensory impairments are quite common as well in CP, ranging from deficits in passive motion sense [15–17], tactile discrimination [18], stereognosis (ability to recognize objects by touch) [15,16,19,20], visuomotor performance, and proprioception impairments. Kinaesthetic deficits occur when patients have trouble reporting the direction, speed, or amplitude of a passive movement. Children with hemiparetic CP typically also exhibit learned non-use of the affected limb due to unilaterally impaired sensory and motor function in the upper extremity [21]. Grasping difficulties in hemiplegic CP may be caused mainly by sensory deficits and difficulties in coordinating sensory and motor information in manual tasks as hypothesized by ref. [22].

Rehabilitation, also referred to as *habilitation*[1] in the case of CP, aims at improving the quality of life and independence of the patients. It has been established that children with CP benefit greatly from periods of intensive physiotherapeutic interventions [23,24]. In that case, children undergo daily or twice-daily therapy sessions, which comes at a great monetary cost [25]. Conventional therapies for CP include physical therapy, occupational therapy, speech therapy, behavioural therapy, medication, and surgery. Research has shown that children often do not find any motivation in conventional therapy [26,27], which can be very repetitive. Moreover, children with CP have overall lower motivation than typically developing children [28]. On the other hand, social robots have been shown to be a great motivator to engage children in educational or therapeutic exercises [29–33]. “Social robots are designed to interact with people in a socio-emotional way during interpersonal interaction [... they] leverage their social and affective attributes to sustain people’s engagement as well as to motivate, coach, educate, facilitate communication, monitor performance, improve adherence to health regimen, and provide social support to people” [34, p. 5368]. Social robots are beneficial for educational purposes, health and therapeutic applications, domestic assistance, entertainment, and companionship, amongst other applications [35]. Robot-assisted therapy, which refers to the use of a robotic device in therapy, can therefore add advantages to therapy for children with CP: robots can be more engaging when coupled with virtual environments, and they can also provide movement kinematics data after each session to monitor progress continuously. Robot[2]-assisted therapy seems particularly suited for such high-intensity,

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[1] See https://napacenter.org/difference-between-habilitation-and-rehabilitation/ for an explanation on the difference between rehabilitation and habilitation.

[2] In this article, we will take the Britannica definition of a robot: “any automatically operated machine that replaces human effort, though it may not resemble human beings in appearance or perform functions in a human-like manner.”

goal-directed training with highly repetitive guided movements. There is a lack of studies involving children with CP, as compared to, *e.g.*, hundreds of publications on robot-assisted therapy for children with autistic spectrum disorders (ASD). It is therefore important to review the current state of this research and provide some recommendations and new research directions to encourage researchers to get involved with this user group.

Previous reviews of robot-assisted therapy for CP mostly focused on lower limbs interventions [36,37] interventions, or the review was made from a medical point of view and does not cover more recent works [26,38], with the sole concern being the therapy's effectiveness. More recently, Blankenship and Bodine proposed a review on socially assistive robots in CP, although they did not focus on motor deficits and excluded medical robots (such as exo-skeletons, orthosis, haptic devices, and end-effector devices) and thus a lot of research that is relevant to this present review [39]. Another noteworthy review on using social robots for children with disabilities did not focus on CP or motor impairments and excluded medical robots, which in the case of motor rehabilitation does not give an accurate view of the state of the art [40].

We are currently developing a project for children with CP where we will be using social robots, as it has been well documented that social robots can increase motivation [29–33,40]. The aim of this scoping review is therefore to explore existing research and identify research gaps to direct future works. The main objective is to identify main trends of upper limb motor rehabilitation for children with CP and how/if the child's motivation and engagement is taken into account. The secondary objective is to identify research gaps and provide recommendations for future research.

2 Methods

2.1 Search procedure

This scoping review is presented according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for scoping reviews (PRISMA-scr) guideline. For this review, we searched the PubMed, Scopus, and IEEE databases, up to October 2021 with the following combinations of keywords: (cerebral AND palsy AND upper AND limbs AND (rehabilitation OR therapy) AND robot). This search yielded 164 results (Figure 1). Articles were first screened using their title, a second screening considered the abstract, and finally the full text was reviewed to determine eligibility. After removal of duplicates, 118 articles remained. After filtering of irrelevant results which contained no robot or CP, therapeutic goal or upper limbs, 65 articles remained. Finally, there were 26 articles left when excluding articles that were not relevant for upper limb rehabilitation. We also searched in English, French and German in Google and Google Scholar.[3] One additional article was identified that way. When several articles referred to the same study, we selected the article which detailed the experimental protocol and results more precisely. For each article, we read the abstract and possibly checked the article for additional information. If the article fit our criteria, it was studied more thoroughly, and its bibliography was searched for additional references.

2.2 Inclusion criteria

The aim of this review is not to review the efficiency of robot-assisted therapy in the present context, but rather to give an overview of what has been attempted, which robots have been used and summarize the efforts to turn a very repetitive form of therapy into engaging and enjoyable sessions for the children. We, therefore, did not use any rigorous exclusion criteria for this review. Thus, our final inclusion criteria were as follows: more than two CP children involved in the study, an identified therapeutic goal to improve motor skills, and some form of objective evaluation, *i.e.*, clinical tests or motion analysis. So after applying the criteria, 13 articles remained.

2.3 Analysis

Search results are presented in Tables 1–3. The studies identified in the preliminary search were first assessed for inclusion by extracting relevant information (number of participants, use of a control group, therapeutic goal). Selected studies were then summarized in terms of participants' characteristics, assessment of motor skills before, during and after the study, duration and frequency of the intervention, therapeutic goal, robot used, tasks performed during the intervention, and efforts to provide an enjoyable experience. The studies were classified according to the therapy goal.

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[3] French search terms: paralysie AND cérébrale AND membres AND supérieurs AND (réhabilitation OR thérapie). German search terms: Zerebralparese AND obere AND ExtremitÃďt AND (Rehabilitation OR Therapie).

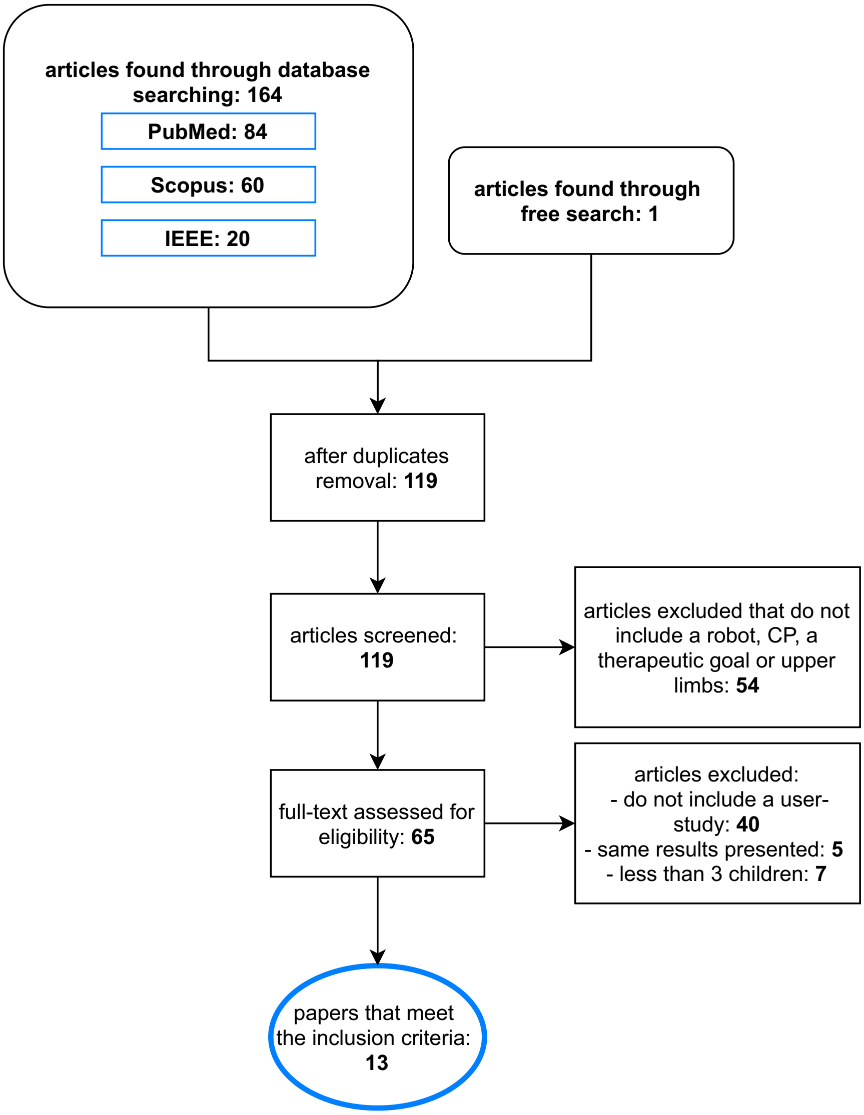

Figure 1: PRISMA Flow diagram of the review process.

3 Results

3.1 Functional upper limb movements

Motor impairments strongly reduce the autonomy of individuals with CP, especially in daily tasks. A predominant goal of therapy is, therefore, to restore some autonomy by improving functional upper limb movements. All the studies presented here (Tables 1 and 2) rely on repetition of motion targeting either functional movements or specific arm joints.

In some cases, the robot is worn by the child as an orthosis, such as the InMotion2 robot [43] and the Armeo-Spring [44] robot, which is an upper limb exoskeleton with seven degrees of freedom and that provides gravitational support thanks to a spring mechanism. It also exaggerates any residual movement for a paretic (paralysed) arm. The Gloreha Sinfonia [45] and the YouGrabber [46] are soft exoskeletons similar to a glove in combination with a dynamic support system, which can detect the movement of each finger and partially or completely supports the movement. There are also several haptic devices or end-effector devices such as the Falcon [47], the Haptic Master [48], the REACHMan [41], and the REAplan [49]. The only robot that does not require physical interaction in this review is the CosmoBot [42,50]. See Figure 2 for an overview of the robots.

Overall, children's engagement, enjoyment, and motivation were not a key concern in any of the reviewed articles. Only two articles [51,52] employed a "socially

Table 1: Summary table on functional rehabilitation using robots

Functional upper limbs movements						
Reference	**Robot used**	**# of subjects with CP (age)**	**# of sessions**	**Task**	**Therapeutic goal**	**Engaging element**
[65]	InMotion2	12 (5–12)	16 × 1 h over 8 weeks	640 repetitive, goal-directed planar reaching movements	Improve motor function in the paretic arm	—
[62]	Haptic Master	9 (10.1)	9 × 1 h over 3 weeks	Perform reaching games	Improve reaching	Game virtual environment
[66]	InMotion2	12 (5–12)	16 × 1 h over 8 weeks	Perform 640 reaching movements	Functional upper limb movement	—
[51]	CosmoBot	6 (5–18)	10 × 20 min over 5 weeks	Perform the desired movement to trigger a reaction from the robot	Functional upper extremity motion (forearm or wrist extension)	Socially assistive robot
[63]	REAplan	8/8 (10.8 ± 4.6/11 ± 3.5)	16 × 45 min RT + 24 × 45 min CT // 40 × 45 min CT over 8 weeks	Perform reaching task in the horizontal plane		Visual interface
[57]	ArmeoSpring	21 (10.8 ± 4.2)	20 × 45 min RT + 20 × 45 min PT over 4 weeks	Perform meaningful tasks targeting different upper arm joints and regions	Improve functional upper limb	Virtual exergame

RT: robotic therapy, CT: conventional therapy, PT: physiotherapy.

Table 2: Summary table on functional rehabilitation using robots (*continued*)

Functional upper limbs movements						
Reference	**Robot used**	**# of subjects with CP (age)**	**# of sessions**	**Task**	**Therapeutic goal**	**Engaging element**
[60]	ArmeoSpring	15/15 (6–8)	36 × 45 min over 12 weeks	Perform customized exercises, involving shoulder, elbow and wrist joints with defined movements (flexion–extension, abduction–adduction and pronation–supination, separated or in combination) in a 1D, 2D, or 3D environment, with increasing demand for accuracy and/or speed	Improve functional upper limb	Virtual environment
[61]	ArmeoSpring	21/15 (7–14)	45 min twice daily over 4 weeks	Perform targeted games wearing the exoskeleton	Improving reach, grasp and transfer movements, active range of motion, force regulation, and initiation of movement	Virtual exergames
[52]	Nao	8 (6.9 ± 2.4)	15 × 25 min over 2 months	Play Mirror and Simon game	Improve gross motor skills	Socially assistive robot

RT: robotic therapy, CT: conventional therapy, PT: physiotherapy.

assistive robot” for non-contact upper limb rehabilitation and put human–robot interaction as the focus of the therapy. In the robotics sessions of ref. [51], children had to perform specific movements that triggered a CosmoBot’s reaction when performed correctly. Children underwent twice-weekly 20-min sessions of robotic intervention for 5 weeks and twice-weekly 20-min sessions of conventional therapy for another 5 weeks. The order of the interventions was randomized. The interventions targeted either forearm supination (roll motion of the forearm) or wrist extension, depending on the children. Motor performance was evaluated before the intervention and after each session using motion capture. Results suggested that the robotics intervention improved targeted movements and that improvement was more significant when the robotic intervention preceded the conventional therapy. There was, however, no significant difference between robotic and conventional therapy in forearm supination or wrist extension improvement. The second article [52] employed a Nao [53] robot to play a Mirror (Imitation game where the children mirror the robot’s movements) and “Simon Says” game (the child obeys the robot’s command if it contains “Simon says”) with the children. They assessed improvement with the QUEST [54,55] and Mallet [56] scales. The QUEST measures dissociated movement, grasp, weight-bearing, and protective extension abilities. The score ranges from 0 to 100 with a higher score representing better quality of movement. Mallet is a test that measures active abduction, external rotation, and movement of the hand to the head, back, and mouth and gives a score between 1 and 25. Their results not only showed motor improvement, but also increased motivation and engagement in the robotics sessions. This is the only article that we found in this review that reported results on engagement and motivation. None of the other studies employ social robots, but several studies used robots coupled with a virtual environment or a visual interface. The ArmeoSpring robot associated with virtual 3D environment was used in ref. [57]. During the robotic sessions, participants played exergames [58] (technology-driven physical activity, usually involving video games) that simulated meaningful tasks (*e.g.*, reaching tasks) targeting different upper arm joints. The therapist adjusted the number of repetitions and level of difficulty of each game according to the patient’s abilities. Patients were evaluated before and after the intervention with the QUEST and the Melbourne Assessment of Unilateral Upper Limb Function. The Melbourne Assessment [59] measures the quality of unilateral upper-limb motor function based on items involving reach, grasp, release, and manipulation in neurologically impaired children. Scoring criteria include range of movement, target accuracy, fluency,

Table 3: Summary table on fine motor skills rehabilitation using robots

Reference	Robot used	Number of subjects with CP (age)	# of sessions	Task	Therapeutic goal	Engaging element
				Hand skills		
[69]	YouGrabber	10/7 (6–18)	12 × 45 min over 3 weeks	Played virtual games	Improving hand grasping and releasing, wrist pronation and supination, and arm reaching	Virtual game
[70]	Falcon Haptic robot (Novint Technologies, Albuquerque, NM	18 children with impairments (3 with CP)	30 min daily over 4–8 weeks	Different writing tasks	Improve fine motor skills	—
[71]	reachMAN2	3 (?)	10 × 15 min over 2–3 weeks	Train pinching, with the index finger and thumb, forearm supination/pronation, and wrist flexion/extension	Improve hand skills	Robot interfaced with an interactive computer game
[72]	Gloreha Sinfonia (Indrogent, Lumezzane, Italy)	7 (6–18)	12 × 60 min over 6 weeks	Task-oriented exercises focus on finger or bimanual movements	Distal upper extremity training	“game modes”

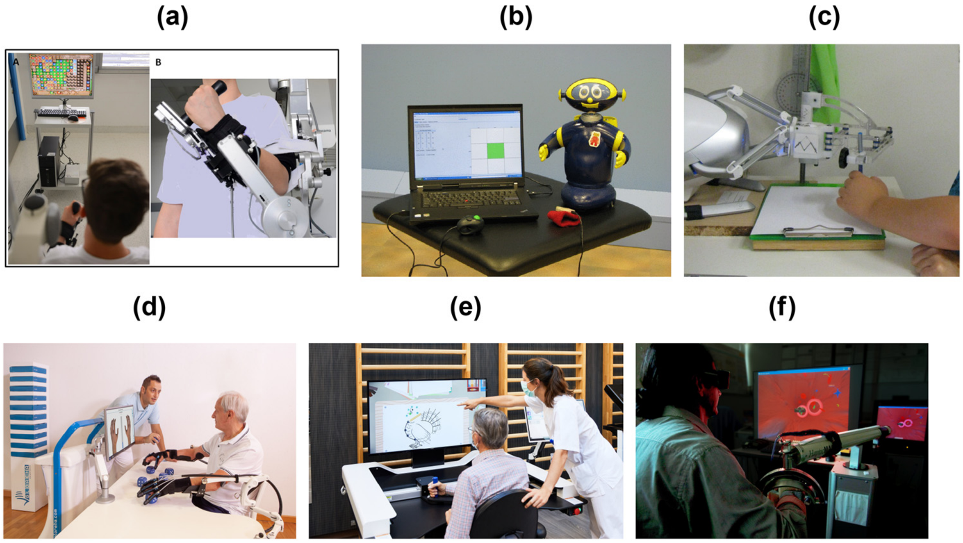

Figure 2: (a) ArmeoSpring (Hocoma AG, Volketswil, Switzerland) (©Emilia Biffi), (b) CosmoBot (AnthroTronix, Inc, Silver Spring, MD, US) [42] (©IEEE), (c) Falcon Haptic device (Novint Technologies Inc., Albuquerque, NM, US) (©: Pamela Hood Szivek), (d) Gloreha Sinfonia (Indrogent, Lumezzane, Italy) (©Indrogent), (e) REAplan (Axinesis, Wavre, Belgium) (©Axinesis), (f) Haptic Master (Moog, The Netherlands) (©Qinyin Qiu).

grasp, accuracy of release, finger dexterity, and speed. The score ranges from 0 to 122 with a higher score representing better quality of movement. The authors noticed significant improvement in terms of velocity, fluidity, and precision of the movement. A second study [60] also used the ArmeoSpring robot and targeted spastic hemiplegic CP. The control group underwent conventional therapy that included passive stretching exercises for elbow and wrist flexors, weight-bearing exercises for the upper limbs, stimulation of the protective reactions of the upper limbs in all directions, strengthening exercises for antagonists of the spastic muscles, and exercises facilitating hand skills. The robotics group performed the games including ArmeoSpring. The games were performed in a 1D, 2D, or 3D environment, with the increasing demand for accuracy and/or speed. The therapist also selected the games to keep the session engaging and enjoyable. Patients were evaluated before and after the intervention with the QUEST and the Modified Ashworth Scale. The authors reported significant improvement of the test scores for the robotics group compared to the control group. A third study [61] used the ArmeoSpring robot, as well, with children with hemiplegic CP. In each session, children performed different exercises in 1D (*e.g.*, goalkeeper), in 2D (*e.g.*, egg cracking, fruit shopping, stove cleaning, moorhuhun and vertical catching), and in 3D (*e.g.*, chase balloon and reveal panorama). Performance was assessed with the QUEST and Melbourne pre-test and post-test. Results showed improved kinematics (smoothness, duration, velocity) for the paretic arm, QUEST and Melbourne scores also improved. In another study, children with hemiplegia, children with spastic quadriplegia, and adults with stroke performed targeted reaching games with the Haptic Master robot in a virtual environment [62]. Assessment of timed tests for forward, sideways, and hand to mouth reaching was performed before and after the intervention. Results showed improvements in reaching tasks and upper extremity functions (path length, duration, and smoothness). Children also improved in sideways reaching. Moreover, the REAplan robot, which is a distal effector robot coupled with a visual interface, allowing for movements in the horizontal plane, has been used in research [63]. During each session, participants performed 744 repetitions of a reaching movement, on average. Abilities were assessed before and after the intervention with the Box and Block test (BBT) and the QUEST test. The BBT [64] measures unilateral gross manual dexterity as the patients need to pick and place as many blocks as possible in 60 s. Smoothness of movement and manual dexterity improved significantly more in the robotics group than in the control group.

Finally, two studies do not explicitly consider children's motivation as there is no engaging element in the therapy [65,66]. They used the InMotion2 robot for children with hemiplegic CP. Children had to perform 640 repetitive reaching movements in each session with their paretic arm, helped by the robot, as needed. In the first study [66], outcomes of the intervention were assessed before, at midpoint, immediately after the program, and 1 month post-completion using the Fugl-Meyer Upper Extremity subscale (FMA-UE), QUEST and motor assessment scale (MAS) scores, parent questionnaire, and robot-acquired kinematic metrics. The FMA [67] measures motor functioning, balance, sensation, and joint functioning. The modified Ashworth Scale [68] grades muscle spasticity between 0 and 4 with a higher score associated with higher stiffness. Results showed significant improvements in the FM, QUEST, and parent questionnaire. Improvements of trained movements in movement duration, aim, deviation from the straight line, and smoothness were maintained post-completion and improvement also generalized to untrained movements. In the second study [65], participants were evaluated twice before the intervention, after 4 and 8 weeks of robotic therapy and 1 month post-completion using QUEST, FMA-UE, MAS, isometric strength, and parent questionnaire. Results showed improvement in QUEST and FMA-UE scores, even in the post-test. The questionnaire also reported the increased use of the paretic arm in functional daily tasks. Isometric strength of elbow extensors improved, too.

3.2 Fine motor skills

Regarding fine motor skills (Table 3), two studies [69,72] used glove-shaped soft exoskeletons with a dynamic support system. van Hedel et al. used the YouGrabber system (YouRehab, Zurich, Switzerland) and children played virtual games (*e.g.*, "toy catching," "catch the carrot," and "tomato juggling") [69]. The control group played computer games. Performance was assessed before and after the intervention with the BBT and the nine-hole-peg test (NHPT) on the affected hand. The NHPT is a standardized test that measures finger dexterity. Results showed an improvement for the robotics group in the BBT. The Gloreha Sinfonia robot has been used for distal upper extremity training [72]. Performance was assessed pre-test, post-test, and at 1-month follow-up using FMA-UE scores and electromyography. There was no engaging element in the proposed therapy. Results showed that the robotic intervention improved the FMA-UE scores for body structure and function domains. In a cube grasping task, mean brachioradialis muscle amplitude and electrical agonist–antagonist muscle ratio also improved, and were maintained at follow-up. The Falcon haptic device was employed in a study aimed at improving fine motor control and writing consistency [70]. The Beery–Buktenica Developmental Test of Visual-Motor Integration – Motor Coordination subtest showed no significant fine motor skill improvement but writing improved. Children's motivation or engagement was not considered in this study. Finally, the reachMAN2 end-effector robot was used with children with hemiplegic CP [71]. Children played an interactive computer game where they had to perform pinching using the index finger and thumb, forearm supination/pronation, and wrist flexion/extension. The Bruininks–Oseretsky Test of Motor Proficiency, Second Edition (BOT2) showed improvement in movement precision, range of motion, and motor skill measurements.

4 Discussion and suggestions for future research

Overall, the included studies had a low number of participants in the robotics group (at most 21). While we acknowledge the difficulties in recruiting participants with disabilities, it is nevertheless important to aim at larger-scale studies to gain deeper insights into the effectiveness of interventions and explore how interventions can be tailored and adapted to different persons and their specific needs and abilities.

Seven studies were not included in this scoping review as the studies included less than three participants. Two of those studies used the InMotion2 robot to improve functional upper limb control [73,74]. Fasoli et al. presented a case study [73] where they combined robotic therapy with the InMotion2 and injections of botulinum toxin type A. The ReachMan robot has been employed in a preliminary study to improve forearm pronation/supination, pinching with the index finger and thumb, and wrist flexion–extension [75]. The other four of those studies included adults [76,77] or young adults [78,79]. It is worth mentioning that adults with CP seem to be mostly overlooked by research in this field that focuses mainly on children. While early intervention is indeed paramount, it should not be forgotten that CP is a progressive disorder and that adults also require ongoing motor therapy, as a "cure" does not exist. Those studies employed the HAL®-SJ robot (Cyberdyne Inc., Ibaraki, Japan) to improve voluntary elbow flexion–extension [79]; a modular power wheelchair to increase autonomy and upper limb control [77]; a haptic device in a labyrinth navigation task to improve coordination, tremor reduction, and movement control [78]; and the MIT Manus (Massachusetts Institute of Technology, Boston, US) [80] preceded by excitatory transcranial direct current stimulation to prime brain motor circuits beforehand, to improve hand function in reaching tasks [76].

Note, two studies tried to use robots that are more “social” and make the interaction with the robot, an integral part of the therapy. The first one [51] used CosmoBot. Here, the children triggered a robot’s reaction if the gesture was performed correctly. However, this study included only a very small number (6) of children. The second study [81] (not included in the review due to the low number of children and lack of a clearly defined therapeutic goal or study) designed a Pacman-like game with small graspable mobile robots. Tasevski et al. hypothesized that the lack of motivation from children stemmed from the fact that therapy does not include collaborative behaviour between the child and the therapist [82], thus designing a robot meant to address those issues. Their preliminary study showed that their robot facilitated not only non-verbal communication and gestures, such as reaching, but also verbal production. Two therapy robots [83,84] were also developed for children with CP, with the main concern of maintaining engagement and motivation. Fridin and Belokopytov used the Nao robot to carry out repetitive training and provide feedback and adapt the exercises based on performance [84]. They reported increased motivation of children with CP and a good involvement in the exercises. Calderita et al. implemented a novel cognitive architecture in the Ursus robot [83]. Their robot can adapt the exercises to each participant, while monitoring and learning from the interaction. They report very attentive and collaborative behaviours from the children interacting with the robot.

While most robotics interventions yielded better results than conventional therapy, the CosmoBot study [51] reported similar results for both. Unfortunately, only one of the reviewed studies included an assessment of engagement or motivation, so it is very difficult to evaluate the motivation/efficiency rapport in all studies. However, if social robots in therapy are as effective as conventional therapy and more engaging, this is definitely a path worth pursuing, as using social robots might not only reduce the cost of therapy, but also offer a more motivating alternative for home exercises, as only about 30% of the patients actually keep up with their program [85]. Also, even if robots that include social elements will be shown to be as cost-effective and efficient as other robotics approaches, the opportunity that they can provide a more engaging and enjoyable experience could improve general well-being and attitudes towards therapy. We truly believe that there is potential to include social robotics more into conventional therapy. In the following, we suggest example scenarios including social robot behaviour that might be suitable for physical or occupational therapy. Note, the proposed scenarios are illustrations and would have to be developed in detail in a co-design approach involving therapists, as well as children with CP and their families. The key approach is to frame the exercises as a game, so from the point of view of the children, they are playing, rather than undergoing therapy (see [86] for guidelines on gamification):

- **Scenario 1**: “Rhythm therapy” (inspired by ref. [87]) – a type of therapy that focuses on repetition and synchronization of movements.
  - *Actors*: A child and a robot
  - *Description*: The task is to perform a rhythmic gesture, such as waving or drumming. First, the child is being told that they can teach the robot gestures: The child performs gestures and the robot coordinates its gestures with the child’s. The robot occasionally asks the child how well it is doing, whether it got the movement correct, *etc*. Second, the child is being told that the robot will teach them gestures. Here, the child is instructed to coordinate with the robot. The robot can detect the quality of the child’s imitative movements and provide verbal and non-verbal positive feedback and encouragement. In another variation, the robot can either randomly or systematically perturb the coordination, so that the children need to adapt their own movements when they imitate the robot. The robot and the child can take turns in the teacher/student roles.
  - *Setting*: The child is placed in front of the robot, either sitting or standing.
  - *Robot*: A humanoid robot, such as Nao or Pepper [88] (Figure 3)
  - *Goal*: Improve motor coordination and gross motor control.
  - *Motivating element*: The robot uses verbal and non-verbal behaviours to engage the child, regularly provides positive feedback, and encourages the child to continue when it detects that the child loses coordination or interest. When the child finishes the task, they can ask the robot to perform a dance, or play music, as a reward.
- **Scenario 2**: “Ball catching/throwing” – exercise commonly used in physical therapy and occupational therapy.
  - *Actors*: Two children and a robot
  - *Description*: One child teleoperates the robot to pick up and shoot balls towards the second child who catches the ball and throws it back at the robot. The children can take turns.
  - *Setting*: The children are sitting or standing in a large area.
  - *Robot*: A robot such as MyJay which is able to pick up and throw balls [89,90] (Figure 3).

  - *Goal*: Improve coordination, improve upper body strength and stability, develop muscles, balance, reaching across the middle of their body and visual motor skills. As a secondary goal, the children will also practise turn-taking and collaboration with each other.
  - *Motivating element*: The children will be playing and collaborating through the robot. The robot provides positive feedback through sounds and lights when a ball is caught or thrown properly. The children can decide when they want to take turns, which encourages communication among them.
- **Scenario 3**: “Dancing” – frequently used in occupational therapy for children with CP.
  - *Actors*: One child or more and one or more robots.
  - *Description*: The robot plays music and dances and the children are encouraged to imitate the robot. The robot can also imitate a child while dancing.
  - *Setting*: The child(ren) standing in a large area.
  - *Robot*: A humanoid robot such as Nao, Pepper or QT [91] (Figure 3).
  - *Goal*: Improve gross motor coordination and body awareness.
  - *Motivating element*: The robot regularly provides positive feedback to the children. The children take turn in choosing the next dance. If the robot detects lower motivation or engagement from one of the children, that child becomes leader of the dance and the robot and other children imitate them. The robot adapts the difficulty of the dance according to the children’s abilities and progress. The robot has a repertoire of songs and dances and the children will be encouraged to try as many as possible, and after each dance, each child gives the robot a score of how well the robot could dance to that song. The dance that receives the highest scores is declared the winner, and the robot will perform the dance again at the end of the class.
- **Scenario 4**: “Table-top activities” – activities frequently used in occupational therapy.
  - *Actors*: One child and a robot.
  - *Description*: The robot and child play games together that target fine motor skills. The robot can either take turns playing with the child (*e.g.*, playing Tic Tac Toe with beads (or other small objects) or play a memory game with article cards) or oversee the activity and provide encouraging feedback, advice, and encouragement (*e.g.*, building structures displayed on a tablet out of marshmallow and toothpicks or Lego’s® or colour in pictures of robots). Note, at present, robots have very limited fine motor skills to do such tasks, so it is more likely that the robot will oversee the activity.
  - *Setting*: The child sitting in front of the robot, with a table between them.
  - *Robot*: A humanoid robot such as Nao, Pepper, or QT (Figure 3).
  - *Goal*: Improve fine motor control (muscle strength, finger isolation, manipulations, thumb opposition, grasping). As a secondary goal, the child could also practise turn-taking with the robot.
  - *Motivating element*: The child can choose the next activity they want to perform with the robot. The activity is led by the robot who either oversees or takes part in the game. The robot provides verbal and non-verbal positive feedback, encouragement, and advice. If the robot detects that the child loses interest, disengages, or shows off-task behaviour, the robot encourages the child to re-focus on the task and may suggest self-regulation strategies, *e.g.*, breathing techniques. Such an approach has been used successfully, *e.g.*, for children with learning disabilities [92].

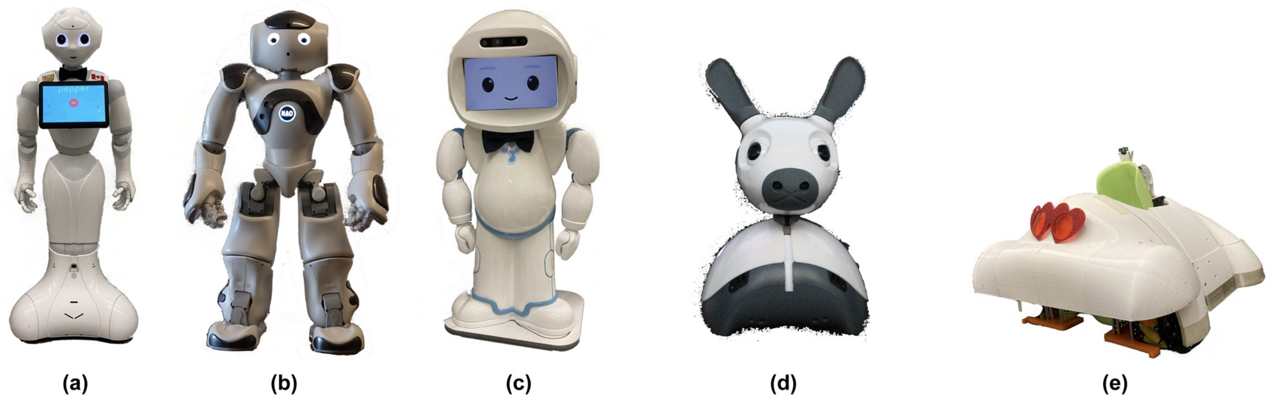
(a) (b) (c) (d) (e)

Figure 3: (a) Pepper (Softbanks Robotics, Paris, France), (b) Nao (Softbanks Robotics, Paris, France), (c) QT (LuxAI, Luxembourg, Luxembourg), (d) Miro (Consequential Robotics, Sheffield, UK), (e) MyJay (University of Waterloo, Waterloo, Canada).

5 Conclusion

In this article, we reviewed robot-based upper limb motor habilitation for children with CP. We found that most therapeutic studies focused on effectiveness of the intervention, which is indeed the most important aspect of therapy. However, another paramount aspect, namely, maintaining children's engagement, enjoyment, and motivation, has often been neglected and can impact effectiveness. We noticed that children with CP usually have to undergo highly repetitive tasks that are perceived by children as boring or unpleasant [27] as they have to perform actions with their impaired limb. Without motivation or a clear perceived goal, children struggle to engage and participate in the therapy. In 12 of the 13 studies, we reviewed, the robot used is very mechanical and functional and is used in very repetitive and very frequent sessions (average 22 ± 12.9 sessions over 5.9 ± 2.8). There has, however, been some effort to make the sessions more enjoyable by coupling the robot with a virtual environment or by designing exergames. We proposed four scenarios as suggestions on how to include enjoyment and motivation in robot-assisted therapy for upper limb impairments in CP. Empirical work is needed to refine and experimentally test those scenarios, in close collaboration with therapists, patients, and other stakeholders.

To summarize, the challenging area of upper limb rehabilitation has been neglected by the Human–Robot Interaction (HRI) community. This is true for upper limb rehabilitation for children with ASD [93] but even more so for children with CP. Note, while there is a great amount of articles developing new robots or technologies for that purpose, they rarely make it to the testing stage. One has to wonder why so many works seemingly get abandoned: Is it the difficulty in finding clinical contacts? or do researchers realize how daunting running that kind of study really is (recruitment, the high number of sessions required, and the clinical pre-, post- and follow up- tests, and so on)? or the lack of funding? In any case, we would welcome a commitment from the robotics, assistive technology, and HRI communities to this population that has been neglected or only been explored in initial attempts, not only concerning CP but also across most motor conditions that affect children. Our review also shows that (re)habilitation of sensorimotor skills (proprioception, touch appropriateness, hand force, *etc*.), hand–eye coordination, bilateral coordination, or imitation have not been covered at all in HRI for children with CP, while they have been explored for other populations, such as children with ASD – with outcomes typically remaining at the level of research prototypes that are not having a lasting and sustained impact on the lives of children with ASD and their careers. To assist children with disabilities, a sustained effort is required to ensure that research prototypes are being translated into actual products that have real-world impact.

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