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RESEARCH ARTICLE

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Building and testing of a robotic intervention framework to enhancing the social engagement of children with autism spectrum disorder

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ABSTRACT

Purpose: Humanoid robot intervention programmes for children with autism spectrum disorder (ASD) are being developed rapidly. This study aimed to develop and test a robotic intervention framework for children with ASD to ensure best practice.
Methods: In Phase I of this study, an initial framework was built based on a scoping review. This review aimed to identify the core elements conducive to effective robotic intervention programmes for children with ASD. In Phase II, the content of the initial framework was verified using a case study approach in a real-life setting.
Results: The robotic intervention framework, which comprised three domains, was built and tested. The three domains were robot-, child-, and programme-related factors. Elements within each domain were identified and verified in real-life contexts.
Conclusions: The proposed framework will enhance evidence-based practice in robotic intervention programmes. However, further clinical testing is warranted to enhance the efficacy and validity of this framework. A good programme design incorporating all essential elements for effective intervention will ensure the success of the training programme for children with ASD.

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Autism; robotics; social engagement; assistive technology; program framework

IMPLICATIONS FOR REHABILITATION

- Contribute to the development of knowledge of and theoretical base for using robotic interventions for children with ASD.
- This study developed a testable program framework and inform researchers about scientific evidence regarding effective use of robotic intervention in the fields of rehabilitation and education.
- Contribute to the advancement of evidence-based practice (EBP) in the field of autism.

Background

Children with autism demonstrate social communication difficulties. According to DSM 5, autism spectrum disorder (ASD) is a neurodevelopmental condition characterised by limitations in social reciprocity and communication and restricted and repetitive behaviour [1]. Individuals on this autism spectrum all share are the social communication difficulties, difficulties with cognitive empathy or theory of mind, the difficulties adjusting unexpected change, usually narrow interests, and sensory hyper- and hyposensitivities [2].

Intervention programmes using human–robot interactions enhance the social participation of children with ASD [3,4]. Unlike human-delivered interventions, robotic interventions offer intrinsically embedded reinforcers that elicit greater social initiation and non-verbal orientation and affect towards the interaction partner [5]. Evidence shows that robotic intervention programmes improve joint attention between instructors and children with ASD [6]. Moreover, stereotyped and repetitive behaviour is less seen during the child–robot interaction [7]. As a result, the social skills of children, including verbal initiation and joint attention, improve over time [8]. A recent meta-analysis of randomized controlled trials demonstrated that robot-mediated interventions significantly enhance social functioning ($g = 0.35$ [95%CI 0.09 to 0.61; $k = 7$) [9]. Nevertheless, effectiveness studies have mainly been case studies with small sample sizes [5]. High-quality results of robotic intervention programmes typically do not appear in journals; rather, they appear in conference proceedings or case reports [10]. Past evidence of using social robots in children with ASD was mainly based on laboratory experiments that focused on basic social skills, such as eye gaze and joint attention [11,12], stereotyped behaviour [7] and imitation [13,14].

Cultivating basic social skills is important for children with ASD. Importantly, such skills should transfer to real-life contexts, with the ultimate goal of improving social participation. Social participation refers to the gain of social roles through participation in social activities [14]. There is less published evidence on the elements of robotic intervention programmes that affect social participation in children with ASD. Participation is described as children's involvement in life situations in the ICF-CY [15]. Social participation is more than the demonstration of basic social skills. Social participation is the feeling of belonging and engagement experienced by the child in relation to being active in a context

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[16]. Past studies in similar areas mainly focused on the component of social skills such as such as joint attention [17] and eye gaze [18]. Moreover, there is no evidence-based framework or protocol to guide the design and implementation of robotic intervention programmes to enhance the social participation of children with autism.

Thus, this study aimed to develop a robotic intervention framework to guide the design of intervention programme for children with ASD, with a goal to enhance their social engagement and communication. A good programme design incorporating the core elements of robotic intervention may ensure training programme success. The followings were the objectives of this study.

1. To identity the core elements conducive to effective robotic intervention programmes for children with ASD.
2. To verify the identified core elements of robotic intervention programmes in real practice.

As such, this study comprised two major phases: (I) formulation of an initial robotic intervention framework based on a scoping review and (II) testing of this initial framework using a case study approach to examine the robotic intervention programme in real-life contexts (Figure 1). The first phase involved a scoping study to map the key concepts and elements underpinned by robotic intervention programmes and the evidence available [15]. The second phase used a case study approach to verify the content of the framework with evidence collected in real practice [16]. The process of framework building in this study was regarded as an ongoing process of comparing data and theoretical assumptions and the continuous refinement between theory and practice.

Methods

Phase I: scoping review to reveal the elements conducive to the best practice design of a robotic intervention programme

The scoping review followed the scoping methodological framework proposed by Arksey and O'Malley [19] and was conducted in six steps [1]: research question development [2]; study identification [3]; study selection [4]; data plotting [5]; data collation and summarisation; and [6] data reporting.

Search strategy

Four databases were searched (CINAHL, PROQUEST, Science Direct and MEDLINE) using 'autism' and 'robot' as keywords. Articles published within 12 years (from 2007 to 2019) were included. The inclusion criteria were full-text conceptual and research articles describing the use of assistive robots as interventions for children with ASD. Articles were excluded if the studies involved children with developmental disabilities without a diagnosis of ASD or only children with typical development, were not published in English or were deemed as grey literature. The research team screened the relevance of the content of each article to deduce the factors associated with effective use of robotic interventions in children with ASD.

Data extraction and analysis

The initial search identified 244 articles. Figure 2 shows the PRISMA flowchart of the step-by-step process of article selection. The methodological quality of the included studies was assessed. Upon removal of duplicate articles, 212 articles were screened according to their titles and abstracts. One hundred seventy-three articles were deemed irrelevant to the research question. The full texts of the remaining 39 articles were screened, and 12 articles that did not meet the criteria were excluded. All these 12 articles were research studies reporting on children with impairments other than ASD, such as cerebral palsy, attention deficit and hyperactivity disorder, motor impairment, speech–language disorder, physical disabilities or other profound/multiple disabilities. A total of 27 studies were included in the final review for thematic analysis. Based on the selected literature, the core elements of robotic intervention programmes were coded and categorised in domains to form an initial framework.

A team approach and researcher triangulation were used to ensure validity and reliability. Two researchers independently reviewed the title, abstract and full text of all selected articles. Reviewers met at the beginning, midpoint and the final stages of the review process to determine the final inclusion of articles. Coding of data and the development of coding chart was an iterative process in which the researchers continually update the coding chart. The process of analysis was overseen and checked by the advisor of this project, who was a professor in special education.

Phase II: verification of framework using a case study approach

Phase II adopted a case study approach to test the framework in real-life settings. Case study research investigated into a real-life phenomenon in-depth within its context. This phase followed the process of case study research to verify a framework [20]. Pattern matching and replication logic were used to verify the elements

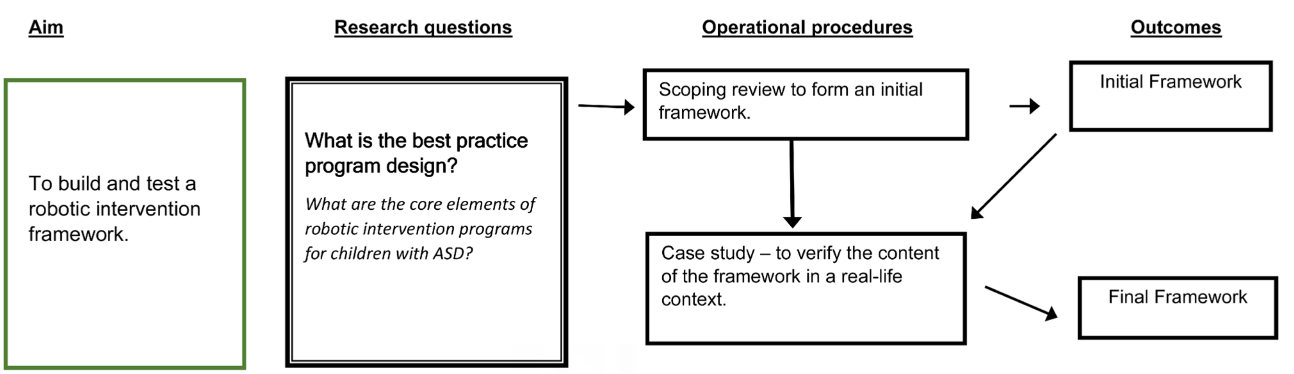

Figure 1. Flowchart illustrating the process of the study. Flowchart depicting the study process, including the aim, research questions, procedures, and outcomes. The flowchart starts with the study aim, followed by the formulation of research questions. It then outlines the procedures undertaken during the study and concludes with the outcomes achieved.

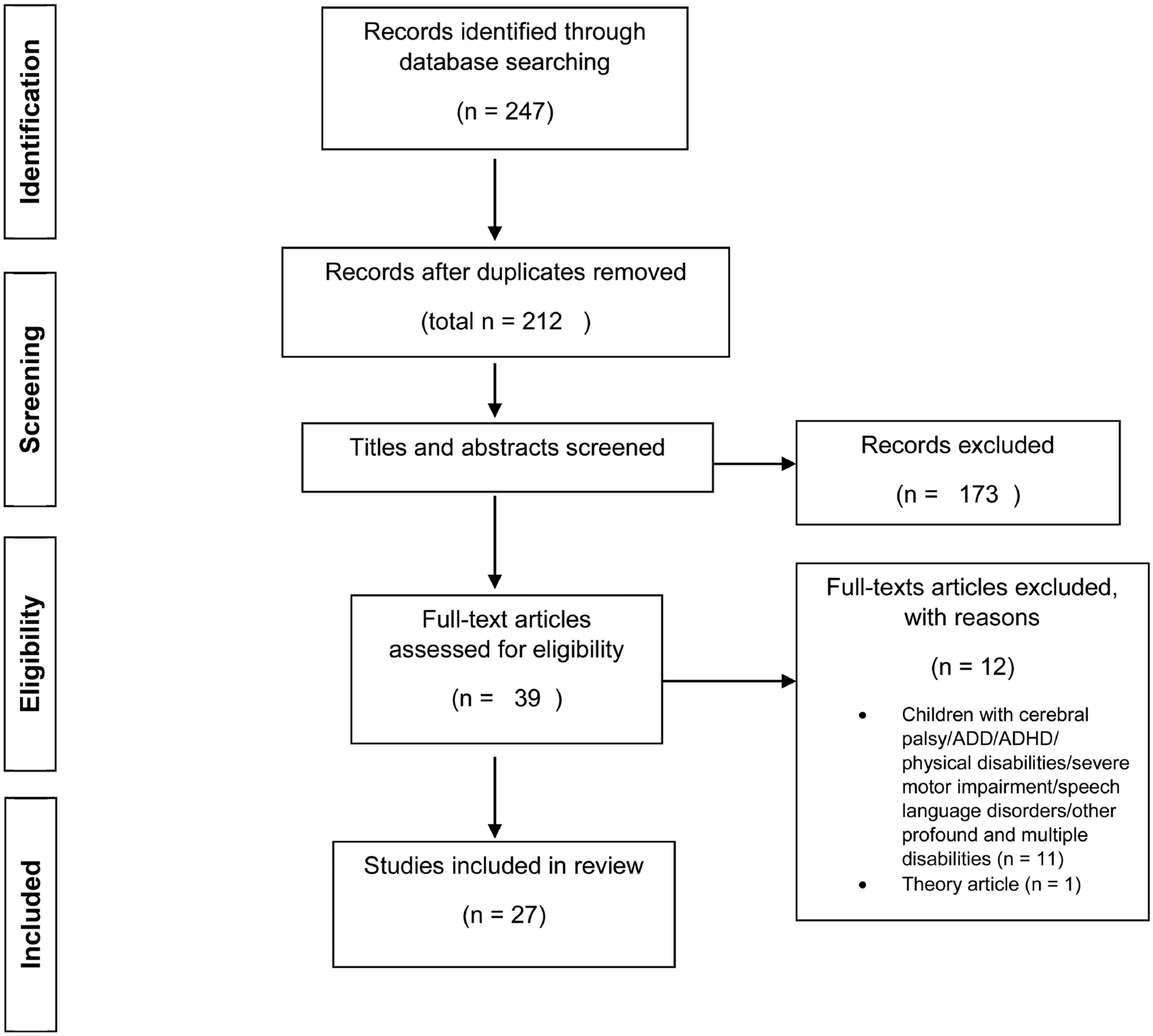

Figure 2. PRISMA flowchart. PRISMA flowchart showing study selection: identification, screening, eligibility, and inclusion, with numbers of records at each stage and exclusion.

of the framework in real practice. Pattern matching involved comparing findings with predicted theoretical patterns and replication logic used multiple cases to test the consistency of findings [21]. A multiple embedded case study was adopted to add reliability to the framework. Multiple cases allowed replication between cases and corroboration of proposition. The embedded case study design helped to examine the robotic intervention programme through pre-selected categories of domains and elements in the framework. The unit of analysis was the robotic intervention activity programme.

Selecting cases

Twenty children with ASD aged between 5 and 11 years were purposefully selected from both special and mainstream schools to ensure variety in their backgrounds. The inclusion criteria followed the diagnostic criteria for ASD as stated in the Diagnostic and Statistical Manual of Mental Disorders, fifth edition, which include deficits in social reciprocity, communication and restricted and repetitive behaviours [1]. Children with ASD were included if they [1] had been diagnosed with ASD and confirmed by a registered psychologist or medical practitioner [2]; had no hearing or visual deficit [3]; could follow simple commands [4]; were aged between 5 and 11 years [5]; had an IQ of ≥ 70 and [6] demonstrated no self-injury or aggressive behaviour. A face-to-face interview was conducted with both the child and their parent(s) to understand the impact of ASD on the child's social participation at home, at school and in the community. The Social Responsiveness Scale (SRS) [22] was used to screen all participants to ensure that they were eligible for the study.

Crafting instrument and protocol

A case study protocol was developed to guide data collection and ensure consistency. Multiple data collection methods were used, including semi-structured interviews, and observations (video recordings of interactions during training sessions). The case study protocol comprised an interview guide, guidelines for video analysis and a data collection template to guide the collection of qualitative data.

A training guide is a training manual that states the operation of all training sessions. The content of the programme followed

Table 1. List of robotic intervention activity programs.

	Activities	Description
1	Follow me	The child takes the robot by the hand, and the robot follows him.
2	Hit the pan	The child instructs the robot to walk and take action to hit the pan.
3	Colour hunter	The child helps the robot to find and name different colours.
4	Math power	The child answers the math quiz as taught by the robot.
5	Story telling	The child listen to the stories as told by the robot.
6	Dancing	The child follows the robot to dance.
7	Football	The child plays simple ball kicking activities with the robot.
8	Song singing	The child sings along with the robot.
9	Guess emotion	The child guesses the emotions as mimed by the robot.
10	Guess sports	The child guesses the sports as mimed by the robot.
11	How still can I be	The child sits still and the robot detects if the child has moved.
12	Walk to the ball	The child uses a ball as a cue to guide the robot walking to different directions.

Table 1 to include all 12 activity programmes from the Ask NAO platform.

The NAO humanoid robot was used to assist the instructor in teaching social skills to children with ASD. NAO is designed to incorporate a wide range of behaviours, including walking, standing up, sitting down and dancing, and recognises speech, sounds and objects [11]. The human instructor-led all sessions, and the robot was programmed to conduct training activities, such as interactive games, dancing and storytelling. The sessions were conducted in Cantonese, which was the native language of the participants. The activities, as carried out by the robot, had been translated into Cantonese and were well-tested in our pilot studies. The human instructor assumed mostly a non-directive role to lead the progression of all activities in the session.

The SRS is a questionnaire that consists of 65 items. It systematically collects information on parents' reports of their children's social awareness, cognition, communication, motivation and mannerisms. The questionnaire has been validated and has high reliability [23]. The Chinese version has also been shown to have good internal consistency (Cronbach's alpha: 0.044 to 0.947), test–retest reliability (intraclass correlation: 0.751 to 0.852) and convergent validity [24].

Entering the field

Participants enrolled in the intervention programme underwent six sessions of robot-assisted social skills training. The program is individual-based and the duration of each session is 30 min. All sessions were conducted by a human instructor and a humanoid robot (NAO) in school settings. The NAO robot was used as an assistant to teach social skills to children with ASD. This study used the NAO robot V5, which is manufactured by Softbank Robotics, and the Ask NAO platform to run the training activities. Activities on the Ask Nao platform were all standardized. Twelve activity programmes from the Ask NAO platform were selected. The purpose of it was not the evaluation of Ask Nao activities. Rather, its aim was to investigate whether the identified core elements of robotic interventions could be found if the activity programme. The list of activities is summarised in Table 1. The duration of each session was 20 min. Two instructors were recruited and trained to conduct the training program using the robot. The backgrounds of these instructors were the graduates from the fields of rehabilitation and psychology. Two robotic intervention activities were conducted to each child in a session (Table 1). The duration of each session was 20 min. Each child was required to participate in six sessions to complete the whole programme. Children and instructors, therefore, had adequate opportunities to experience all 12 activity programmes.

Data were collected via semi-structured interviews and video analyses. Parents, children and instructors were interviewed upon completion of the training programme. Their perceptions of the elements in the robotic intervention programmes were explored during these interviews. Specifically, their perceptions on the three domains (i.e. use of robot, child's compatibility, and program implementation) were asked in the interviews. All sessions were videotaped to map the elements in the initial framework.

Analysing data

First, all interviews with participants were transcribed. Second, multiple sources of evidence collected from the 12 robotic intervention programmes were collated and analysed using pattern matching and replication logic [21]. Collected data were linked to propositions by formation of a case description table. Data from all sources were aggregated to determine the occurrence of elements and domains across the 12 robotic intervention programmes. These findings were put into a programme summary table. Items (elements and descriptions of activity) that could not be classified into the original framework were considered new elements to be added into the framework.

Results

Phase I: formulation of an initial framework based on the scoping review

Twenty-seven papers were included (Table 2). The majority of these studies ($n=21$) were original research papers. The other types were review ($n=3$) and concept ($n=3$) papers. Among the original research papers, 17 were quantitative studies, 4 were qualitative studies and 3 used mixed methods. All studies included children with ASD; however, some studies also included children with typical development or other types of disability. Fifteen different types of robot were used across the 21 research studies, including NAO, Rovio, Keepon, Pleo, Roball, Robota, Tito, GIPY-1, Isobot, Probo, Alice-R50, iRobiQ, CARO, KASPAR and COLOLO. The majority of studies used the NAO robot in their intervention programmes ($n=12$). Commonly studied behavioural outcomes in robotic intervention programmes were eye contact, joint attention and reciprocal interaction.

The initial framework

The results of the analysis show that three categories of core elements related to effective robotic intervention were collated [1]: robot selection [2]; participant characteristics and [3] activities and instructions.

Robot-related factors, the program is effective if the robot can: provide simple and real-time experience to demonstrate custom-made behaviour to suit different scenarios [7, 11]; be programmable to conduct a structured, interactive session [7, 25]; can provide both practice and reinforcement [11]; with both closed-loop and human-mediated system [12]; demonstrate both cognitive and social skills [11]; interact and play games with people with both verbal and nonverbal behaviour [26]; and be human looking [26].

Child-related factors included level of intelligence [7]; perception on attractiveness of the robot [7, 13, 27]; social abilities in interaction with people or robots [22, 28–30]; levels of social

Table 2. Articles included in the scoping review.

Authors	Title	Nature of paper	Key findings
1. Shamsuddin et al. 2012	Initial Response in HRI: a case study on evaluation of child with autism spectrum disorders interacting with a humanoid robot NAO	Research	Robotic interventions dampened the autistic traits in the forms of stereotyped behaviour, communication and social interaction
2. Shamsuddin et al. 2014	Design and ethical concerns in robotic adjunct therapy protocols for children with autism	Conceptual paper	A flow chart consisting of 10 important stages is proposed as guidelines for robotic intervention programs.
3. Anzalone et al. 2014	How children with autism spectrum disorder behave and explore the 4-dimensional (spatial 3D + time) environment during a joint attention induction task with a robot	Research	NAO is less engaging than a human partner and even less for children with ASD. With the NAO robotic platform, both groups of children (typically developed and ASD groups) showed lower performances during the three phases of tasks. While interacting with the NAO robot, the children with ASD scored with a lower JA score as compared the TD children.
4. Bekele et al. 2014	Pilot clinical application of an adaptive robotic system for young children with autism	Research	Participants in both the ASD and TD control groups spent a higher percentage of time looking toward the robot as compared to the human administrator. Children in both groups (the ASD and TD control) required more prompt levels for accurate response in the robot conditions than the human conditions.
5. Dautenhahn 2007	Socially intelligent robots: dimensions of human-robot interaction	Conceptual paper	Addressed the different dimensions of HRI. Discussed the requirements on social skills for robots and introducing the conceptual space of HRI studies. Applications in HRI was explored.
6. Ueyama 2015	A bayesian model of the uncanny valley effect for explaining the effects of therapeutic robots in ASD	Research	The effects of robot-assisted therapy in children with ASD is tested. Human-looking robots may have potential advantages for improving social interactions in children with ASD.
7. Ioannou et al. 2015	Pre-schooler's interest and caring behaviour around a humanoid robot	Research	Pre-schoolers can easily interact with the humanoid robot. A systematically developed coding scheme capturing the verbal and non-verbal behaviour was produced. Humanoid robots can evoke feelings in children.
8. Srinivasan et al. 2015	The effects of rhythm and robotic interventions on the Imitation/Praxis, Interpersonal Synchrony and motor performance of children with ASD: a pilot RCT	Research	Robotic interventions improved in praxis/imitation, interpersonal synchrony among children with ASD.
9. Costescu et al. 2015	Reversal Learning Task in Children with ASD: a robot-based approach	Research	Children with ASD are more engaged in the task when interacting with the robot. They demonstrated similar cognitive flexibility in the robot and human conditions.
10. Warren et al. 2015	Can robotic interaction improve joint attention skills?	Research	Improved in ability to orient to prompts administered by the robotic system. Children continued to display strong attention toward the humanoid robot over time.
11. Warren et al. 2015	Brief report: development of a robotic intervention platform for young children with ASD	Research	Children with ASD exhibited greater attention to robotic system than human administrator. imitation performance fore ASD children appeared superior during the robotic sessions
12. Standen et al. 2016	Adapting a humanoid robot for use with children with profound and multiple disabilities	Research	Suggestions were made on how to use robots to work with children with disabilities.
13. Kim et al. 2013	Social Robots as Embedded Reinforcers of Social Behaviour in Children with Autism	Research	Heightened verbalization during the robot condition was resulted. It may reflect the effects of the robot as am embedded reinforcer.
14. Michaud & Laplante 2007	Perspectives on mobile robots as tools for child development and pediatric rehabilitation	Research	Imitation of body movements and familiar actions occur more frequently with the human instructor rather than the robot. Attention sharing and imitation of facial expressions occur more frequently with the robot. The children figured out that the robot was teleoperated, which generated enthusiastic interactions between the child and the experimenter.
15. Giannopulu & Pradel 2010	Multimodal interactions in free game play of children with autism and a mobile toy robot	Research	Children with autism showed greater interest in playing with the robot.
16. Srinviasan et al. 2013	Effect of interactions between a child and a robot on the imitation and praxis performance of typically developing children and a child with auitsm: a preliminary study	Research	The child with autism had improved his imitation of robot actions during the robot-led condition as well as the imitation of human actions in the generalized test of praxis.
17. Simut et al. 2016	Children with autism spectrum disorders make a fruit salad with probo, the social robot: an interaction study	Research	Children had more eye-contact with the robot than with the human partner, no differences were found between the two conditions with regard to the other social behaviors. Children with ASD did not differ in detecting the preferences of the robot or the adult.
18. Srinivasan et al. 2016	The effects of embodied rhythm and robotic interventions on the spontaneous and responsive social attention patterns of children with ASD: a pilot randomized controlled trial	Research	The robot group engaged in greater self-directed vocalization compared to the other groups. The comparison group engaged in greater social verbalization compared to the robot group.
19.Taheri et al. 2018	Clinical interventions of social humanoid robots in the treatment of a pair of high-and low-functioning autistic Iranian twins	Research	No significant improvement was shown in the child with low-functioning autism in terms of social skills, but the amount of stereotyped & detrimental behaivors reduced during the course of the program. Communication between the two participants improved.
20. Perez-Vazquez et al. 2019	Evaluation and Identification from a Bibliometric Perspective of the Use of Robots in the Intervention of Children with ASD	Review	Vast majority of studies express positive results from working with robots in students with ASD. Increased interaction with humans after working with robots. Common outcomes are improved social skills such as expressiveness or facial expression.

(*Continued*)

Table 2. Continued.

Authors	Title	Nature of paper	Key findings
21. Yun et al. 2017	Social Skills Training for Children with Autism Spectrum Disorder Using a Robotic Behavioural Intervention System	Research	Eye contact percentage significantly increased in both groups (human therapist and robot-assisted). Better improvement in eye contact as compared to the human therapist. Percentage of correct answer for facial emotional recognition increased in a similar pattern for both groups, with no difference between the 2 groups.
22. So et al. 2018	Robot-based intervention may reduce delay in the production of intransitive gestures in Chinese-speaking pre-schoolers with autism spectrum disorder	Research	Participants with ASD who received robot-based gestural training produced intransitive gestures more accurately in training stories than those who did not receive training. Similar patterns were found in non-training stories, suggesting that acquired gestural production skills could be generalized to novel stories.
23. Sartorato et al. 2017	Improving therapeutic outcomes in autism spectrum disorders: enhancing social communication and sensory processing through the use of interactive robots	Conceptual paper	A ranged of robots were examined. Enhanced sensory processing and integration of robotic social cues may underline the perceptual and behavioural benefits that brought by robot-assisted therapy.
24. Mengoni et al. 2017	Feasibility study of a randomised controlled trial to investigate the effectiveness of using a humanoid robot to improve the social skills of children with autism spectrum disorder (Kapar RCT): a study protocol	Research	A protocol was produced for further testing.
25. Matsuda et al. 2017	Facilitating Social Play for children with PDDs: Effects of Paired Robotic Devices	Research	Frequency of eye contact and positive affect for all children with ASD did not consistently increase or decrease in the with automatic feedback condition. Increase in eye contact and positive affect were observed in 2 children in the *without* automatic feedback condition.
26. So et al. 2016	Using robot animation to promote gestural skills in children with autism spectrum disorders	Research	After controlling for visual-motor coordination skills, significant difference are found between the pretests and posttest in gestural skills. The positive outcomes were maintained 2 weeks after the training, and children were able to generalize the acquired gestures to novel setting with human beings.
27. DiPietro et al. 2019	Computer-and robot-assisted therapies to aid social and intellectual functioning of children with autism spectrum disorder	Review	Outcomes being evaluated included emotion and face recognition, eye contact, speech vocalization, and pragmatic application, social interactions, collaborative play behaviors, executive function abilities, task performance, imitation, social attention patterns and engagement, social relationship development, repetitive behaviors, and positive and negative affect. Effectiveness of these interventions varied across the studies. The majority of the studies demonstrated some level of encouraging results, limitation are noted in several studies.

participation as demonstrated by the preferred play types [7]; and motor skills which included postural control, gait pattern and bilateral coordination skills [31,32].

Program-related factors were identified as: the efficacy of the intervention partner or the human instructor [7, 11,12, 33]; sufficient prompting by the human instructor [22]; assumptions of the robotic intervention program: caretaker paradigm or the companion paradigm [20]; program operated in socially embedded movement-based contexts [14]; the program content is attractive and easily understood [29]; social feedback embedded in the program as administered *via* technology [5]; the program is structured, standardized and gradable [34]; and it is conducted in an integrative environment [35].

Phase II. Verification of framework in the real context

Phase II used the case study approach to test the content validity of framework. Twenty children participated in the intervention programme: 18 boys and 2 girls. These children were aged from 5 to 11 years, with an average age of 8.15 years (standard deviation [*SD*] = 1.90). The mean SRS score of the 20 children was 76.2 (*SD* = 13.95), which indicated a deficiency in reciprocal social behaviours that might lead to severe interference with everyday social interactions [20].

Observations in the 12 programmes for checking of elements in the framework

Evidence as shown in the observations was mapped against the elements and domains of the framework. Consolidated findings from the observation in the 12 programmes are shown in Table 3, which illustrates the elements presented in each activity programme. The within-case analysis shows the profile of each programme. The directions of singing and storytelling activities were found to be one way. Limited interaction and absence of appropriate feedback and reinforcement were associated with these two activities. The across-case analysis demonstrated that most elements in the initial framework were present in the programmes. However, the elements named 'human-mediated operation' and 'gradation' were absent in all of the activity programmes in the Ask NAO platform. In terms of matching the elements of the framework with real-life practice, two items not originally included in the initial framework emerged from the analysis [1]: compatibility with cultural background and [2] adequate attention and concentration. The frequency of data matching with these elements demonstrated their prominence in the robotic intervention programmes.

Collating evidence from multiple sources to verify the framework

Review of the framework, placement of new elements into the framework and review of the robotic intervention programmes were required. The two new elements were placed under the domain of child-related factors (Table 3). Use of the activity protocols in the Ask NAO platform was insufficient because the elements of gradation and human-mediated operation were not present. When considering the newly added elements, the programme was required to be culturally relevant and to capture and maintain the child's attention. Due to limitations in the two activities (singing and storytelling), we were required to modify

Table 3. Mapping of elements of the framework to the activity programme.

		Activity program											
		follow me	Hit the pan	colour hunter	Math power	Story telling	Dancing	Football	Song singing	Guess emotion	Guess sports	How still can I be	Walk to the ball
Domain 1	**Robot characteristics and presentation**												
1.1	Simple in appearance and looks approachable	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
1.2	Embedded with different interaction scenarios/ modules	x	x	✓	✓	x	x	x	X	✓	✓	x	x
1.3	Provides feedback and feedforward	✓	✓	✓	✓	x	x	✓	x	✓	✓	✓	✓
1.4	Involves use of combined senses	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
1.5	Involves both automatic and manual operating systems	x	x	x	x	x	x	x	x	x	x	x	x
1.6	Demonstrates predictable behaviours	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
1.7	Provides cues, prompts and reinforcement	✓	✓	✓	✓	x	x	x	x	✓	✓	✓	✓
1.8	Receptive	✓	✓	✓	✓	x	x	✓	x	✓	✓	✓	✓
1.9	Acts as a role model	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
1.10	In real-time	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
1.11	Gradation	x	x	x	x	x	x	x	x	x	x	x	x
1.12	Possesses human-like features	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
1.13	With movement or locative capacity	✓	✓	✓	x	✓	✓	✓	x	✓	✓	✓	✓
1.14	Allow filtering / amplifying of meaning perceptual stimuli	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
1.15	User-friendly and easy to operate	✓	x	✓	x	✓	✓	x	✓	x	x	✓	✓
Domain 2	**Participant characteristics**												
2.1	Compatible cognitive ability	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2.2	Compatible communication ability	✓	✓	✓	✓	✓	✓	✓	x	✓	✓	✓	✓
2.3	Compatible language	x	✓	✓	✓	✓	x	x	x	✓	✓	✓	✓
2.4	Compatible motor skills	✓	✓	✓	x	x	✓	✓	✓	x	x	✓	✓
2.5	Sensory and behavioural stability	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2.6	Comfortability	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Domain 3	**Activities and instructions**												
3.1	Presence of a human instructor	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
3.2	Facilitation skills	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
3.3	Positive regard	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
3.4	Structured and interactive	x	✓	✓	✓	x	x	x	x	✓	✓	✓	x
3.5	Fun	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
3.6	Precise and concise	✓	x	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
3.7	Social feedback	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
3.8	Natural interactions and communication	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
3.9	Balanced interaction between the robot and human	✓	x	x	x	x	x	✓	x	x	x	✓	x
3.10	Integrative environment	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
3.11	Appropriate length	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
New elements													
2.7	*compatible with cultural background*			✓		✓					✓		
2.8	*adequate attention and concentration*	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Table 4. The final framework.

Domain 1 Robot-related factors – robot selection	
1.1.	Simple in appearance and looks approachable [7, 25].
1.2.	Embedded with different interaction scenarios/modules [25].
1.3.	Provides feedback and feedforward information to encourage practice and reinforce performance [11].
1.4.	Involves use of combined senses and enables sensory learning *via* multisensory channels, such as visual, tactile and auditory senses [11, 27, 31].
1.5.	Involves both automatic and manual operating systems/both closed-loop and open-loop systems [5, 12,13, 25, 28, 32].
1.6.	Demonstrates predictable behaviours in response to a stimulus, action or instruction [7, 14].
1.7.	Provides cues, prompts and reinforcement and provides verbal and non-verbal communication cues, offers praise and prompts, provides human-like social cues and has embedded intrinsic reinforcers [5, 11, 13, 26, 28].
1.8.	Receptive (contains sensors to capture information, such as touch and sound) [11,12].
1.9.	Acts as a role model by demonstrating social, motor or cognitive skills [3, 26, 31].
1.10.	Receives and processes information and gives responses in real-time [5, 11, 13].
1.11.	Has an adapted interface to cater to the diverse levels of function among children (gradation) [34].
1.12.	Possesses human-like features [26].
1.13.	Possesses joint movement or locative capacity (movement and degree of freedom) [14].
1.14.	Works as a mediator to simplify, amplify or filter meaningful stimuli or information [3, 31].
1.15.	User-friendly and easy to operate and no requirement for an add-on device [12, 31, 36].
Domain 2 Child-related factors – participant characteristics	
2.1.	Compatible cognitive ability: The child can follow and comprehend the robot's instruction to complete games or activities [7].
2.2.	Compatible communication ability with intact hearing and vision. The child can follow verbal and non-verbal instructions from the robot, without severe receptive language impairment (4,7.25).
2.3.	Compatible language: The child's language is compatible with that of the robot [25].
2.4.	Compatible motor skills: The child possesses adequate motor control to complete motor or gestural tasks [27].
2.5.	Sensory and behavioural stability: The child has no significant behavioural or sensory problems that may hinder safe participation in the programme [4, 32].
2.6.	Comfortability: The child likes robots and shows a clear interest in playing or working with them [7, 32].
2.7.	Compatible with cultural background#.
2.8.	With compatible level of attention and concentration#.
Domain 3 Program-related factors – Activities and instructions	
3.1.	Presence of a human instructor/interaction partner: The instructor acts as a 'comfortable presence' to the child [7].
3.2.	Facilitation skills: The efficacy of the programme depends on the facilitation skills of the human instructor, with sufficient prompting and guidance [11].
3.3.	Positive regard: The human instructor gives positive reassurance, praise and reinforcement [33].
3.4.	Structured and interactive: The programme is built upon rationale, provides structured sessions, which promote and encourage interactions [25].
3.5.	Fun: The programme is fun, interesting and attractive to the child [4].
3.6.	Precise and concise, with a clear target: The activity is straightforward and easy to understand, and the expected responses/actions from the child are clearly defined [30].
3.7.	Social feedback: Social feedback is embedded in the programme activities and administered by technology [5, 30].
3.8.	Natural interactions and communication: The programme and activity design simulate social settings and environments [14].
3.9.	Balanced interaction between the robot and human: A balance between time spent on attending to the robot and to the human interactive partner (or instructor) is incorporated [4].
3.10.	Integrative environment: The programme is stress-free and enables the robot to be integrated into the social environment [35].
3.11.	Appropriate length: A sufficient number of sessions and an appropriate session duration are set to ensure effectiveness [4].

Note. #Newly found element.

these two activities so that they could be more interactive and reinforcing. The singing activity was modified to include a brief greeting and an introduction. The robot was programmed to encourage the child to sing and dance, while the storytelling activity was modified to suit the local culture of the child. Cantonese was used as the medium of instruction, which was intended to facilitate interaction between the child and robot. This could be mediated by the human instructor to allow for a longer conversation between the child and the instructor. The final framework is shown in Table 4, and it comprised 3 domains and a total of 34 elements.

Discussion

Promoting evidence-based practice

This study aimed to strengthen evidence-based practice regarding robotic interventions for children with ASD. The framework provides a guide to good practice. This study systematically built and tested a framework to inform therapists, teachers and practitioners on the essential elements and domains to be considered in the planning and delivery of robotic intervention programmes. The conventional approach to robotic intervention programmes considers mainly the technical use of robotics for intervention. This study emphasises the consideration of all essential factors related to the child, the programme and the use of robots, which all contribute to an effective robotic intervention programme. All elements in the three domains should be included in the intervention programmes to ensure a good practice.

Domain 1 considers robot characteristics and presentation. The selection of robots for use in intervention programmes is of utmost importance. Although a variety of robots have been used in published research, it does not indicate that only sophisticated robots, such as NAO, Pepper or Milo, should be recommended for use in the program. A balance should be achieved between function and practicality. Robots should be user-friendly and manageable to users [31, 36]. Robots work to simplify, amplify or filter meaningful stimuli or information in intervention programmes [3, 31]. It is preferable for robots to be simple in appearance, approachable [7, 25], predictable and able to provide embedded feedback and feedforward to children [5]. Provision of sensory cues and stimulation to children by the robot is also important [11, 27, 31]. Robots should also possess certain degrees of freedom to enable physical movement. This will help to encourage imitation and motor responses from children. Robots can act as role models to demonstrate and perform targeted tasks or behaviours [14]. Incorporation of both automatic and manual modes in the programme is useful to facilitate learning [5, 12,13, 25, 28, 32]. Moreover, adaptability and gradation help to cater to children with diverse levels of learning and functional needs.

Domain 2 considers the participant's characteristics. Each child's level of functioning should be compatible with that of the robot and the programme involved [7]. Children need to process adequate cognitive, motor and social skills to interact effectively with robots [4, 25,26, 29]. Some robotic intervention programmes may even require an advanced level of cognitive functioning and language ability. As shown in Phase II of this study, when using the Ask NAO platform to administer the robotic intervention activities, participation was limited by individual language skills and cultural backgrounds. The NAO robot can be programmed to speak and receive different languages. However, most robots can recognise only fluent English speech.

Domain 3 considers the program activities and instructions. This domain is concerned with how the human instructor plans and implements the intervention activities using the robot. The human instructor is the primary leader of the intervention programme and leads the programme with the aid of the robot. The robot is thus regarded as an assistive device. The instructor should be able to conduct a structured activity programme for children with ASD [30]. Effective use of facilitation skills by the human instructor will ensure programme effectiveness [11,12]. The instructor may use verbal and physical prompts to encourage the child to initiate and sustain a triadic interaction with the robot and the human interaction partner. The instructor should facilitate the child–robot interaction by allowing sufficient time for the child to respond. Verbal praise and positive reassurance are required to encourage the child to participate actively and purposefully in the programme. Moreover, the programme activities should be fun and engaging [4]. Natural interactions and communication between all parties should be achieved during the activity session. This may simulate daily interactions in real-life settings to enhance generalisation. The session can be conducted in individual or group mode depending on the objectives of the session. Children with ASD should be encouraged to achieve a balance between interacting and playing with both the robot and with other human interaction partners.

Strengths and limitations of this study

Reconciling evidence across activities, users and instructors and using a mixed source of data for triangulation enhanced the empirical validity of the framework in this study. Robotic intervention programmes impact the social development of children with ASD. These programmes are complex in nature, and they involve multi-dimensional skillsets to design, plan, implement and evaluate. The traditional approach may focus on either the technical use of robots or the change in component skills of participants when interacting with robots. This study attempted to integrate these multi-faceted dimensions to build a framework. The framework was built based on evidence and verification in real-life settings using a case study approach. The strength of this approach is reconciliation of the ambiguity between theory and reality [20].

There are, however, some limitations to this study. When verifying the elements of the three domains in real-life settings, we used mostly the activity programmes on the Ask NAO platform because this platform was the only standardised programme available in the market for the NAO robot. There are also other humanoid and animated robots. Thus, future studies may test this framework using other robots to further enhance its validity. The effectiveness of programmes adopting this framework could be further tested using a quantitative or experimental approach, which may further validate the framework's reliability and internal validity.

Conclusion

This study developed a framework to describe the factors that contribute to best-practice robotic intervention programmes. Evidence-based practice and users' perceptions of robotic intervention programmes were explored and documented in this study to enhance the quality of practice. The developed framework could be further tested and applied in different settings to ensure the effectiveness of robotic intervention in children with ASD.

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Compliance with ethical standards

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was obtained from all individual participants included in the study.

Ethics approval and consent to participate

Ethical approval from the Human Research Ethics Committee of The Education University of Hong Kong was obtained (2017-2018-0131). All participants were given informed consent for participation in this study.

Consent for publication

Not applicable

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Notes on contributors

Eva Yin-han Chung was the principal investigator. She contributed to develop the theoretical framework, research design, coordinate data collection, perform data analysis and interpret results, as well as the writing of the manuscript.

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Data availability statement

The datasets generated and/or analysed during the current study are not publicly available because consent and approval was not obtained for sharing of subject data from participants or the Committee on the Use of Human and Animal Subjects in Teaching and Research.

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