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Robot-Based Motor Rehabilitation in Autism: A Systematic Review

Melanie Jouaiti · Patrick Hénaff

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Abstract A growing number of studies investigate robot intervention in the case of Autism. Most of these studies are either focused on social skills or robot design. However, a large number of autistic children also suffer from motor deficits which are directly correlated with impaired communication skills and severity of autism. While several robot-centered reviews or reviews interested in social robotics for autism have already been made, a review on robot-based motor rehabilitation in autism was still lacking. In this paper, we dedicate our review to motor rehabilitation in autism, notably using robots. To do so, we searched the PubMed, IEEE, PsycNet and Science Direct databases. We show that although this research is promising, it has been neglected and would benefit from more consideration. The goal of this review is to highlight the relevance of past work and insist on the dire need to develop this research.

Keywords autism · motor coordination · therapeutic robotics · motor rehabilitation

1 Introduction

The first description of Autism Spectrum Disorder (ASD) was realized by Kanner in 1943. ASD is an umbrella term with different manifestations of autism at various levels of severity (formerly Kanner's autism, Asperger syndrome, high functioning autism).

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As of 2018, the prevalence of ASD is estimated at 1.7 % of the population (2.7 % of boys and 0.67 % of girls). Diagnosis of ASD has been increasing for decades, but there is no consensus whether this is the result of increased awareness, improved detection, expanding definitions, increase in incidence or a combination of all these factors. Diagnosis now relies on the DSM-V (Fifth Edition of the Diagnosis and Statistical Manual of Mental Disorders, 2013). It highlights two areas of impairment: social communication and behavioral domain which can be rated by level of severity. ASD is usually associated with a wide range of comorbidities such as developmental coordination disorder (DCD), attention deficit hyperactivity disorder (ADHD), obsessive compulsive disorder (OCD), gastrointestinal symptoms...

ASD cannot be "cured" but abilities can be enhanced thanks to different types of therapy. Early intervention is thus paramount. Several robot-centered reviews have studied adequacy of robot design and robot abilities. The goal of those reviews is to determine the required components for an interaction which would elicit engagement in ASD children. This is not our goal, this review is focused on motor rehabilitation for ASD and particularly using robots. For a robot-centered review, see Huijnen et al. (2016); Cabibihan et al. (2013).

Though a myriad of studies on motor rehabilitation for stroke, Parkinson or Cerebral Palsy exist, these studies have rarely been extended to Autism Spectrum Disorders (ASD). Moreover, most of the child - robot interaction studies present important methodological limitations. Some have no therapeutic goal, but only observe what happens. Even when the study has a clearly identified goal, few have a control group and realize follow-up tests to evaluate the actual effectiveness. So for this review, we attempted to impose some exclusion

criteria for the articles to be included: they had to have a control group of non-ASD children and more than two children in each group. Since we focus on therapy-oriented papers, an identified therapeutic goal, a pre-evaluation and a post-evaluation of motor skills were required. However, since only few papers fit the criteria, we had to be less demanding.

In this work, the PubMed, IEEE, PsycNet and Science Direct databases were searched with the following combinations of keywords: ($\{\text{autism} \mid \text{ASD}\} \& \{\text{motor} \mid \text{movement}\} \& \{\text{rehabilitation} \mid \text{therapy} \mid \text{intervention}\} \& \text{"robot"}$) | ($\{\text{autism} \mid \text{ASD}\} \& \{\text{imitation} \mid \text{coordination} \mid \text{tactile} \mid \text{touch} \mid \text{haptic}\}$). The goal of this review is to highlight the relevance of past work and insist on the dire need to develop this research. We show that although this research is promising, it has been neglected and would benefit from more consideration and from a rigorous methodological approach.

The paper is organized as follows: in the second part of this paper, we present motor impairments in ASD, then in the third part, we talk about the different types of robot-therapy for motor rehabilitation in ASD. Finally, we discuss and conclude this paper.

2 Motor Impairments in ASD

Impaired motor functioning has been consistently observed by parents and clinicians (see Peña de Moraes et al. (2017) for a review of impaired motor learning in ASD). It involves mostly general clumsiness in gait (Biffi et al., 2018; Dufek et al., 2017; Rinehart et al., 2006a,b; Vernazza-Martin et al., 2005), balance (Molloy et al., 2003), manual dexterity (Kushki et al., 2011; Alaniz et al., 2015), praxis (Abu-Dahab et al., 2013; Rodgers et al., 2019; Sacrey et al., 2014; Glazebrook et al., 2006; Nazarali et al., 2009) and coordination (Curioni et al., 2017; Xavier et al., 2018; David et al., 2009; Romero et al., 2016).

Studies also reported that severity of motor skill impairments was directly correlated with severity of social and communication impairments (MacDonald et al., 2014; Dziuk et al., 2007; Manwaring et al., 2017; Dadgar et al., 2017; Higashionna et al., 2017; Jasmin et al., 2009; Purpura et al., 2016; Hilton et al., 2012; Goldman et al., 2009) since motor skills are a paramount part of social communication and can impact the understanding of others' actions (Gallese et al., 2013). Cummins et al. (2005) showed that autistic children with motor deficits had less empathy and greater social difficulties.

34 to 79 % of the autistic population (opposed to 5% of the typical population) is affected by Developmental Coordination Disorders (DCD) (Kopp et al.,

2010). This involves nervous tics, laterality disorders, tip-toeing, synkinesis, catatony, oculomotor disorders, diadochokinesis, dysgraphia, inappropriate manual force, low digital speed and slowness of dexterity. Overall 80% - 90% of children with ASD show some degree of motor abnormality (David et al., 2009; Dziuk et al., 2007; Ghaziuddin and Butler, 1998; Hilton et al., 2012; Ming et al., 2007; Provost et al., 2007).

Motor control is classically divided into motor planning in the higher levels and execution in the lower levels. Besides, movement execution involves connections between multiple brain regions. First, the prefrontal cortex communicates with the basal ganglia and decides the motor strategy based on sensory information (auditory, visual, somatic, proprioceptive). Then the primary motor cortex, supplementary motor area and the cerebellum compute the muscle activation sequence to perform the task. It is believed that the angular and supramarginal gyri are the site of storage of learned time-space movement representations which help to program the premotor cortex. Finally, the premotor cortex is involved in translating movement representations into motor programs, which then activates the motor cortex for execution. The motoneurons and spinal interneurons generate the movement and adjust it, if needed.

A crucial step in motor learning is the ability to form internal models (Krakauer and Shadmehr, 2007), i.e. predict the consequences of motor commands and learn from errors to adapt. The cerebellum is a site for acquisition of internal models and it has been observed in post-mortem exams that the cerebellum is indeed abnormal in individuals with ASD (Williams et al., 1980; Ritvo et al., 1986; Bauman and Kemper, 2005; Bailey et al., 1998; Fatemi et al., 2002). However, Larson et al. (2008) showed that ASD children had no problem acquiring new internal models, thus hypothesizing that the dysfunction stems from another region (basal ganglia, frontal or parietal) or from connectivity abnormalities between regions (Balsters et al., 2018). Indeed, low activation of the cerebellum and motor execution networks also occurs in motor coordination tasks (Mostofsky et al., 2009). Autism is characterized by hypo-functioning of the connections in the higher level of the brain (connection between the frontal lobe and the rest of the cortex) and hyper-functioning at the lower level. It has thus been hypothesized that the decreasing cerebellum activity could evidence a difficulty to transmit motor execution from the cortical regions to the areas associated with "automated" motor execution (Stoit et al., 2013; Oldehinkel et al., 2018; Schipul et al., 2011). Over-connectivity between the thalamus and cortical sensory processing areas (Traynor et al.,

2018; Mizuno et al., 2006), as well as between basal ganglia and somatosensory and motor cortices has also been reported (Traynor et al., 2018; Di Martino et al., 2011; Turner et al., 2006; Cerliani et al., 2015). MRI studies have shown microstructural compromise in motor, sensory and cerebellar pathways (Nair et al., 2013; Carper et al., 2015; Sivaswamy et al., 2010; Hanaie et al., 2013; Nair et al., 2015). Recently, altered white matter has been discovered in the left somatosensory area and its descending pathways connecting to the cerebellum (Lin et al., 2019).

Besides, fMRI studies have reported reduced volume in the fastigial nuclei and cerebellar vermis lobules VI-VII. This region is responsible for ocular motor function, verbal working memory and speech coordination.

However, in ASD, implicit motor learning ability remains intact (Nemeth et al., 2010; Izadi-Najafabadi et al., 2015; Gordon and Stark, 2007). Implicit motor learning is defined as the acquisition of motor skills without conscious access to what was learned or even to the fact that learning occurred. Explicit motor learning occurs when the goal and the execution are plainly explained to the children. So children can exhibit a clumsy gait when consciously walking and walking becomes smooth when they focus on another task.

Moreover, imitation is an essential part of child development. It can be defined as the replication with retention of certain characteristics of an observed motor act by an individual. Imitation follows the observed act. While contributing to social learning, it also plays a critical role in the development of Theory of Mind, social cognition and communication skills. A popular belief is that ASD individuals lack Theory of Mind. Theory of Mind is the ability to attribute mental states to oneself and to others as well as understand that others have different mental states from one's own. It also involves inferring that those states can cause action (Baron-Cohen et al., 2001; Heyes, 2001). Jones et al. (2018) showed that there is an association between lack of Theory of Mind and restricted repetitive behaviors (motor stereotypies).

In the case of ASD, there is a controversy concerning imitation deficits (Xavier et al., 2015; Rogers et al., 2010b; Vivanti et al., 2011; Salowitz et al., 2013; Vanvuchelen et al., 2011; Vivanti et al., 2014; Sowden et al., 2016) and the broken mirror theory which postulates that a deficient motor neuron system (MNS) contributes to imitation deficits (Southgate and Hamilton, 2008). The MNS encompasses regions in the inferior frontal gyrus and the inferior parietal lobule. It is involved in both the movement production and action observation (Rizzolatti and Craighero, 2004; Guillot et al., 2009). While some researchers

reported autism-specific impairments in imitation (Meltzoff, 1993; Rogers and Pennington, 1991) and a dysfunctional MNS (Iacoboni et al., 2005; Oberman and Ramachandran, 2007), others showed intact ability to engage in imitation (Hammes and Langdell, 1981; Press et al., 2010; Bird et al., 2007), preserved action representation and thus a functional MNS (Chen et al., 2018; Carmo et al., 2013; Hamilton et al., 2007). However, neuroimaging studies evidenced that neural activity and connectivity in regions for imitation may be abnormal in ASD (Bernier et al., 2007; Dapretto et al., 2006). Nishitani et al. (2004) examined oral-facial imitation in TD (Typical Development) and ASD using magnetoencephalography (MEG). They observed neural activity that temporally progressed from the primary visual cortex (V1) to the superior temporal sulcus (STS) to the inferior parietal lobule (IPL) to the inferior frontal gyrus (IFG) and finally to the primary motor cortex. Similar activation was observed in both TD and ASD participants, but activation was weaker and delayed in IFG for the ASD group. Villalobos et al. (2005) also found decreased functional connectivity between V1 and IFG bilaterally in a fMRI study where they investigated interregional synchronization with visual areas.

Vanvuchelen et al. (2011) postulated that imitation deficits can be explained by either an impairment in the selection mechanism due to a poor preferential attention to biological motion and in recognizing intentional actions or by an impaired correspondence mechanism due to a poor viewpoint transformation and visuomotor mapping.

Furthermore, some individuals with ASD are hypersensitive. Their touch can be inappropriate since they do not have correct sensory feedback and they can unwillingly hurt other persons (Foss-Feig et al., 2012). On the other hand, others present hypersensitivity and can be overwhelmed by touch (Blakemore et al., 2006; Riquelme et al., 2016). Tactile interaction could be a useful communication tool to complete inadequate verbal skills. Caldwell (1996) even suggests that touch can replace defective means of communication.

Studies have also endeavoured to make robots "autistic" by reproducing the motor deficits observed in order to better design motor rehabilitation studies. Idei et al. (2018) investigated the effects of increased and decreased sensory precision on adaptive motor behaviors. They showed that aberrant precision leads to behavioral rigidity. Barakova and Chonnaramutt (2009) studied the temporal aspect of sensory precision with a mobile robot. They predicted that grasping is performed properly by ASD children except in the presence of proximal obstacles.

3 Method

3.1 Search Procedure

For this review, we searched the PubMed, IEEE, PsycNet and Science Direct databases with the following combinations of keywords: ({autism | ASD} & {motor | movement} & {rehabilitation | therapy | intervention} & "robot") | ({autism | ASD} & {imitation | coordination | tactile | touch | haptic}). This search yielded 2550 results. After removal of duplicates and irrelevant results, we selected 53 papers. When several papers referred to the same study, we selected the paper which detailed the experimental protocol and results more accurately. For each paper, we read the abstract and possibly looked into the paper for additional information. If the paper fit our criteria, it was studied more thoroughly and its bibliography was searched for additional references. Eight papers were selected by browsing through the references.

3.2 Inclusion Criteria

We attempted to impose some rigorous exclusion criteria for the articles to be included: they had to have a control group of ASD children and more than two children in each group. Since we focus on therapy-oriented papers, an identified therapeutic goal, a pre-evaluation and a post-evaluation of motor skills were required. However, since only three papers fit the criteria, we had to be less demanding. Thus our final inclusion criteria are as follows: more than two ASD children, an identified therapeutic goal to improve motor skills and some form of objective evaluation. So after applying the criteria, twelve papers remained.

3.3 Data Extraction

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, significance of the outcome of the intervention. The studies were classified according to their primary goal: improve coordination, imitation, fine motor skills, sensorimotor skills.

4 Robot-based Motor Rehabilitation in Autism

Motor skills can be tackled from different points of view as they encompass a wide range of skills: fine motor skills, gross motor skills, motor coordination, motor imitation, sensorimotor skills. Research studies usually focus on one specific skill. See Table 1 for an overview.

4.1 Coordination

Moorthy and Pugazhenti (2016) used a custom-made LEGO snatcher robot to enhance psychomotor skills in ASD children. They had 20-30 minutes weekly sessions for an undetermined period. Five ASD children participated in the study and imitated the robot in four different activities which basically consisted in turning and picking up a basket. This imitation task was meant to improve non verbal imitation, hand-eye coordination, balanced body movements and backward walking. The children's progress was assessed thanks to success rate and therapists' testimony. It was reported that the children had been able to generalize the concept of pick and place and had improved eye-hand coordination.

So et al. (2018) used the Nao robot to tell social stories while gesturing. Fifteen ASD children participated in the intervention condition in four 30-minutes sessions. They were instructed to imitate the robot gestures (fourteen intransitive gestures). They had control groups of fifteen ASD children and fifteen TD children. Results showed improvement of accurate or appropriate intransitive gestures for the intervention group and also that gestural production accuracy became similar to the TD group. The intervention group also produced more verbal markers while gesturing. Moreover, they found that gestural recognition skills were correlated to the learning ability of gestural production accuracy. Before the study, language and communication abilities and motor skills were assessed by the Psychoeducational Profile, Third Edition (Schopler, 2005) and the BOT2 test. Delayed BOT2 post-test showed that progress was maintained.

Srinivasan et al. (2015) compared rhythm and robot intervention (Nao and Rovio) with thirty-six ASD children. The children were divided into three groups: robot, rhythm intervention and control group. Each group engaged in joint action-based gross motor and/or fine motor activities that promoted social skills (eye contact, turn taking, greeting and imitation) as well as communication skills. The rhythm and robot groups promoted balance, coordination, interpersonal synchrony, imitation and manual dexterity. The control group focused on fine motor skills. Training lasted

eight weeks and four sessions were provided each week. Motor skill deficits were assessed with the MABC-2 test (Movement Assessment Battery for Children Henderson and Sugden (1992)) and evolution was followed with the BOTMP-2 (Bruininks-Oseretsky Test of Motor Proficiency (Bruninks, 1978)). They observed more negative behaviours in the robot and rhythm groups but the frequency decreased over the weeks for the rhythm group. Negative behaviours can be explained by the fact that the activities in those groups were highly unconstrained, which generated a lot of stress for the children. However, there was no improvement for the robot group. The authors attributed this to poor robot performance.

According to this paper, rhythm therapy should be favoured as long as robots are so technically restricted, especially on the movement generation side. Indeed, in long-term interventions, children tend to grow bored of such limited robots.

4.2 Imitation

Robots have been extensively used in ASD children-robot interactions to observe imitation abilities (Boucenna et al., 2014; Bugnariu et al., 2013; Conti et al., 2015). While Pierno et al. (2008) observed that seeing a robot movement elicits a faster movement to grasp a ball than seeing a human movement in ASD children, Bird et al. (2007) showed that ASD adults imitate the hand of a robot more often than the hand of a human.

Greczek et al. (2014) studied the influence of graded cueing feedback to improve imitation with twelve ASD children during five sessions over the course of 2.5 weeks. Six children received maximum feedback while the others received adaptive feedback depending on their performance. They computed imitation accuracy using a Kinect sensor and showed that graded cueing lead to non-decreasing trend in imitation accuracy compared to the non-adaptive condition. Moreover, Zheng et al. (2016) also used the Nao robot with eight ASD and eight TD children. They were asked to imitate a robot or a human raising one hand, raising two hands, waving and reaching arms out to the side. They evaluated accuracy of imitation using a Kinect. They observed more engagement when the child interacted with the robot and better imitation improvement in the robot session for the ASD children than in the human condition. The typical children, however, showed no significant improvement. Ali et al. (2019) designed a study to improve joint attention and imitation, which they tested with twelve ASD children across eight sessions over six months. The children

observed two robots imitating each other and then had to imitate one of the robots performing arm gestures. Success rate from the Kinect and EEG data were assessed. The paper focuses mainly on joint attention, for which it shows improvement, there was however no improvement in imitation skills. Beer et al. (2016) combined music therapy with the Nao robot to improve imitation with four ASD children over the course of six weeks. The robot was integrated to the regular music therapy sessions of the children. The robot performed dance moves in accordance with the therapy music. They observed an increase in frequency of imitating the robot dance and a decrease in therapist's prompts.

4.3 Fine Motor Skills

Srinivasan et al. (2015) used the robot Nao and the mobile robot Rovio in a motor rehabilitation study. They had thirty-six ASD children divided into three groups: control, rhythmic and robot groups. The control group did table top activities to develop fine motor skills. The rhythm group performed whole-body discrete imitation and interpersonal synchrony-based rhythmic games with music. The robot group performed dual and multilimb imitation and synchrony-based games. The aim for the latter groups was to improve balance, bilateral coordination, imitation, interpersonal synchrony and manual dexterity.

So et al. (2019) endeavoured to improve fine motor skills in a study where a robot or a human (control group) engaged in daily life conversations and demonstrated fourteen intransitive gestures to twenty-three ASD children. The intervention lasted nine weeks. It started with a pre-test (BOTMP2) and post-tests were performed immediately after the training and two weeks after to assess the generalization effect. Results showed that the robot acting as a teacher was as effective as the human. However, children in the robot group were more likely to engage eye-contact with the teachers. Gestural production improved for both groups.

Palsbo and Hood-Szivek (2012) used a haptic robot

Reference	Robot used	Number of ASD Subjects (age)	Control Group	Task	Therapeutic Goal	Efficiency Evaluation
Imitation	Nao	12 (7.96 ± 2.36)	0	Imitate the robot performing arm movements	Improve joint attention and imitation	EEG and Kinect Analysis of video data
	Nao	4 (11 ± 3.56)	0	Children imitate the robot performing dance moves	Improve imitation	imitation accuracy
	Nao	12 (7-12)	0	Imitate the robot. The robot gives feedback to the child and corrects the child	improve imitation	imitation accuracy
	Nao	8 (3.83 ± 0.54)	8 (3.61 ± 0.64)	Imitate robot or experimenter raising one hand, raising two hands, waving, and reaching arms out to the side	improve imitation	imitation accuracy
Coordination	LEGO snatcher robot	5 (4 - 10)	0	Children imitate the robot in 4 activities	Improve non verbal imitation, hand-eye coordination and balanced body movements and backward walking	Evolution of success rate
	Nao	15 (4 - 6)	15 ASD and 15 TD children	Nao narrates five stories and gestures. ASD children were told to imitate the gestures	improve motor skills	PEP-3 and BOTMP2
	Nao & Rovio	12 (7.6 ± 2.2)	12 doing table top activities & 12 undergoing rhythm therapy	Rhythm group: whole-body discrete imitation and interpersonal synchrony-based rhythmic games with music; robot group: dual and multilimb imitation and synchrony-based games	Improve balance, bilateral coordination, imitation, interpersonal synchrony, and manual dexterity	MABC-2 & BOTMP2

Table 1 Summary table on imitation rehabilitation using robots. (BEERY-VMI: Beery-Buktenica Developmental Test of Visual-Motor Integration; PEP: Psychoeducational Profile; MABC: Movement Assessment Battery for Children; CARS: Childhood Autism Rating Scales)

Reference	Robot used	Number of ASD Subjects (age)	Control Group	Task	Therapeutic Goal	Efficiency Evaluation
Moorthy et al. (2016)	Snatcher robot	8 (?)	0	recognize left/right robotic shoe and close velcro	enhance the psychomotor skills like pincer grasp, hand-eye coordination and bilateral coordination	pre-test & post-test
Palsbo and Hood-Szivek (2012)	Haptic robot	18 children with impairments (5 with ASD)	0	Different writing tasks	Improve fine motor skills	BEERY-VMI test
So et al. (2019)	Nao	12 (9.17 ± 1.29)	11 ASD children interacting with a human	Robot or Human engaged in daily life conversations and demonstrated 14 intransitive gestures	improve fine motor skills	BOTMP2
Costa et al. (2015)	Kaspar	8 (4-15)	0	perform different activities with the robot (based on identification of body parts and imitation)	improve touch, awareness of body parts	pre-test & post-test
Robins and Dautenhahn (2014)	Kaspar	24 (6-9)	0	perform a tactile game with the robot	improve touch appropriateness	pre-test & post-test
Lee et al. (2014)	ifbot	8 (11 ± 2.56)	0	achieve required force and maintain it until the end of the test	improve control of hand force with and without robot feedback	post-test success rate

Table 2 Summary table on fine motor skills and sensorimotor rehabilitation using robots. BEERY-VMI: Beery-Buktenica Developmental Test of Visual-Motor Integration; PEP: Psychoeducational Profile; MABC: Movement Assessment Battery for Children

to improve fine motor skills of eighteen children with motor impairments (AHDH, attention deficit disorder, cerebral palsy and ASD) including five children with ASD. They underwent 15-20 daily sessions of 25-30 minutes each over 4-8 weeks. The children performed different writing tasks designed according to their writing difficulties (slowness, reversed letters...). They also performed robot-assisted glyph formation. Progress was assessed with the BEERY-VMI test. For the ASD children, progress was observed in writing speed and letter reversal. The therapy was however ineffective for children under age 9.

Moorthy et al. (2016) developed a shoe-like robot to teach ASD children to recognize left and right shoe and improve fine motor skills when closing a velcro band. When properly closed, positive visual feedback was provided. They tested the system with eight ASD children over four consecutive daily sessions. They performed pre-tests and post-tests which consisted in identifying real shoes, recognizing the left and right one and closing the velcro band. They observed improvements in this everyday task.

4.4 Sensorimotor Skills

Robins and Dautenhahn (2014) used the Kaspar robot to teach appropriate tactile behavior. The children could explore touch and interaction and were able to perform inappropriate behavior. The robot reacted to touch and indicated inappropriate behavior or hurtful contact. The authors observed that the children became more aware of their force and started paying attention to their actions.

Costa et al. (2015) also used a robot to teach eight ASD children, across seven sessions of ten minutes, how to use the appropriate force when physically interacting with a partner and the awareness of their body parts. The robot successfully acted as mediator and they observed increased triadic interaction. Inappropriate force also decreased compared to the first session.

Lee et al. (2014) designed a study to improve control of hand force using a sphere which could change colour. Eight children had to apply the required force and maintain it until the end of the test. They performed the experiment with and without feedback from the ifrobot. The experimenters observed success rate as well as target keeping. Authors reported that children performed better with robot feedback.

5 Conclusion

In this paper, we reviewed robot-based motor rehabilitation for ASD children. We remark that most therapeutic studies are focused on improving emotion or social skills. While those are obviously an issue and should be extensively studied, motor skills should not be neglected since they are directly correlated with severity of communication skills and hence of ASD and DCD is indeed a prominent comorbidity of ASD. However, so far, there are very few sound studies proposing a therapy to improve motor skills.

Here is a list of the shortcomings that could be observed:

- The studies are studies on small groups of children (average: 9.27 ± 5.52)
- Vast heterogeneity in the process and the results making it extremely difficult to compare or evaluate
- Dubious choice of evaluation methods when clinical motor assessment tests exist. These tests should be performed before the intervention, at regular intervals during the intervention and at the end of it
- No use of control group or evaluation on typical children. One group should interact with the robot and another undergo another form of therapy to sensibly demonstrate that robot-therapy for motor rehabilitation is more effective than usual methods
- It is rarely taken into account whether the children already have another treatment and how it might affect the motor therapy
- There is seldom a follow-up to check if the skills have been retained

Moreover, while many studies observe children behaviour and assess deficits, few propose a therapy. There exists several possibilities for motor rehabilitation, such as exercise therapy, rhythm therapy, occupational therapy, technology-based therapy (augmented reality, virtual reality...). However few seem to be exploited to their full extent. Indeed, while there is a significant amount of research in motor rehabilitation for stroke, spinal cord injuries, Parkinson or cerebral palsy, those studies rarely extend to ASD. Despite compelling arguments (Janzen and Thaut, 2018; Tryfon et al., 2017; LaGasse and Hardy, 2013b; Jamey et al., 2019), rhythm rehabilitation still is dauntingly underdeveloped for ASD. It has indeed been observed that despite cerebellar abnormalities, individuals are still capable of motor entrainment and synchronization. Moreover, engaging in short rhythmic motor activities leads to brain plasticity and involves structural and functional changes in the brain (Luft et al., 2004). In spite of a regain of interest in the

last few years, motor rehabilitation for ASD is also still particularly neglected in the robotics field and would benefit from more rigorous methodology and from scientists willing to involve themselves in that problematic. Even when the research aims to help and improve skills, it seldom has a clearly identified goal and it is rarely methodologically sound. Indeed, most experiments have very few subjects, no control groups and no follow-up test to evaluate improvement. A lot of studies also rely only on parent questionnaires and have no objective assessment despite the existence of recognized tests such as the BOTMP. Finally, it is very hard to quantify efficiency since other interventions underwent by the children at the same time are not always taken into account and there is rarely long-term control. While most studies inspire themselves from ABA or TEACCH, few combine exercise therapy, rhythm therapy or even occupational therapy with robots. We understand that exercise or occupational therapies might be complicated due to robot limitations but we feel that combining the efficacy of rhythm rehabilitation and the engagement ASD children have with robots may be a very promising perspective.

Finally, most research employing robots is robot-centered and focuses on what design, which features to endow the robot with. This perspective was not reviewed. We do not think that the design of the robot is the most paramount aspect of the problem since children react similarly to a theatrical robot or to an actual robot. However, Srinivasan et al. (2015) suggested that children could get bored due to robot technical limitations. Robot-oriented research is also an important aspect but a lot is already being done in this field. Instead of focusing on making an engineering contribution, it is high time research was oriented towards a more human goal.

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References

- Abu-Dahab SM, Skidmore ER, Holm MB, Rogers JC, Minshew NJ (2013) Motor and tactile-perceptual skill differences between individuals with high-functioning autism and typically developing individuals ages 5–21. *Journal of autism and developmental disorders* 43(10):2241–2248
- Alaniz ML, Galit E, Necesito CI, Rosario ER (2015) Hand strength, handwriting, and functional skills in children with autism. *The American journal of occupational therapy : official publication of the American Occupational Therapy Association* 69 4:6904220030p1–9
- Ali S, Mehmood F, Dancey D, Ayaz Y, Khan MJ, Naseer N, de Cassia Amadeu R, Sadia H, Nawaz R (2019) An adaptive multi-robot therapy for improving joint attention and imitation of ASD children. *IEEE Access*
- Bailey A, Luthert P, Dean A, Harding B, Janota I, Montgomery M, Rutter M, Lantos P (1998) A clinicopathological study of autism. *Brain: a journal of neurology* 121(5):889–905
- Balsters JH, Mantini D, Wenderoth N (2018) Connectivity-based parcellation reveals distinct cortico-striatal connectivity fingerprints in autism spectrum disorder. *NeuroImage* 170:412 – 423, DOI <https://doi.org/10.1016/j.neuroimage.2017.02.019>, segmenting the Brain
- Baraka K, Melo FS, Veloso M (2019) Interactive robots with model-based ‘autism-like’ behaviors. *Paladyn, Journal of Behavioral Robotics* 10(1):103–116
- Barakova EI, Chonnaramutt W (2009) Timing sensory integration. *IEEE robotics & automation magazine* 16(3):51–58
- Baron-Cohen S, Wheelwright S, Hill J, Raste Y, Plumb I (2001) The “reading the mind in the eyes” test revised version: A study with normal adults, and adults with asperger syndrome or high-functioning autism. *Journal of child psychology and psychiatry* 42(2):241–251
- Bauman ML, Kemper TL (2005) Neuroanatomic observations of the brain in autism: a review and future directions. *International journal of developmental neuroscience* 23(2-3):183–187
- Beer JM, Boren M, Liles KR (2016) Robot assisted music therapy: A case study with children diagnosed with autism. In: *The Eleventh ACM/IEEE International Conference on Human Robot Interaction*, IEEE Press, pp 419–420
- Bernier R, Dawson G, Webb S, Murias M (2007) EEG mu rhythm and imitation impairments in individuals with autism spectrum disorder. *Brain and cognition* 64(3):228–237
- Biffi E, Costantini C, Ceccarelli SB, Cesareo A, Marzocchi GM, Nobile M, Molteni M, Crippa A (2018) Gait pattern and motor performance during discrete gait perturbation in children with autism spectrum disorders. *Frontiers in Psychology* 9:2530, DOI 10.3389/fpsyg.2018.02530
- Bird G, Leighton J, Press C, Heyes C (2007) In-tact automatic imitation of human and robot actions in autism spectrum disorders. *Proceedings of the Royal Society of London B: Biological Sciences* 274(1628):3027–3031

- Blakemore SJ, Tavassoli T, Calò S, Thomas RM, Catmur C, Frith U, Haggard P (2006) Tactile sensitivity in asperger syndrome. *Brain and cognition* 61(1):5–13
- Boucenna S, Anzalone S, Tilmont E, Cohen D, Chetouani M (2014) Learning of social signatures through imitation game between a robot and a human partner. *IEEE Transactions on Autonomous Mental Development* 6(3):213–225
- Janzen TB, Thaut MH (2018) Rethinking the role of music in the neurodevelopment of autism spectrum disorder. *Music & Science* 1:2059204318769639, DOI 10.1177/2059204318769639
- Bruninks R (1978) Bruninks Oseretsky test of motor proficiency: Examiners manual. Minnesota: American Guidance Service
- Bugnariu N, Young C, Rockenbach K, Patterson RM, Garver C, Ranatunga I, Beltran M, Torres-Arenas N, Popa D (2013) Human-robot interaction as a tool to evaluate and quantify motor imitation behavior in children with autism spectrum disorders. In: 2013 International Conference on Virtual Rehabilitation (ICVR), IEEE, pp 57–62
- Cabibihan JJ, Javed H, Ang M, Aljunied SM (2013) Why robots? a survey on the roles and benefits of social robots in the therapy of children with autism. *International journal of social robotics* 5(4):593–618
- Caldwell P (1996) Getting in touch: Ways of working with people with severe learning disabilities and extensive support needs. Pavilion
- Carmo JC, Rumiati RI, Siugzdaite R, Brambilla P (2013) Preserved imitation of known gestures in children with high-functioning autism. *ISRN neurology* 2013
- Carper RA, Solders SK, Treiber J, Fishman I, Müller RA (2015) Corticospinal tract anatomy and functional connectivity of primary motor cortex in autism. *Journal of the American Academy of Child and Adolescent Psychiatry* 54 10:859–67
- Cerliani L, Mennes M, Thomas RM, Di Martino A, Thioux M, Keysers C (2015) Increased functional connectivity between subcortical and cortical resting-state networks in autism spectrum disorder. *JAMA psychiatry* 72(8):767–777
- Chen YT, Tsou KS, Chen HL, Wong CC, Fan YT, Wu CT (2018) Functional but inefficient kinesthetic motor imagery in adolescents with autism spectrum disorder. *Journal of autism and developmental disorders* 48(3):784–795
- Conti D, Di Nuovo S, Buono S, Trubia G, Di Nuovo A (2015) Use of robotics to stimulate imitation in children with autism spectrum disorder: A pilot study in a clinical setting. In: *Robot and Human Interactive Communication (RO-MAN)*, 2015 24th IEEE International Symposium on, IEEE, pp 1–6
- Costa S, Lehmann H, Dautenhahn K, Robins B, Soares F (2015) Using a humanoid robot to elicit body awareness and appropriate physical interaction in children with autism. *International journal of social robotics* 7(2):265–278
- Cummins A, Piek JP, Dyck MJ (2005) Motor coordination, empathy, and social behaviour in school-aged children. *Developmental medicine and child neurology* 47 7:437–42
- Curioni A, Minio-Paluello I, Sacheli LM, Candidi M, Aglioti SM (2017) Autistic traits affect interpersonal motor coordination by modulating strategic use of role-based behavior. *Molecular Autism* 8(1):23, DOI 10.1186/s13229-017-0141-0
- Dadgar h, Alaghand Rad J, Soleymani Z, Khorammi A, Maroufizadeh S (2017) Relationship between motor, imitation and, early social communication skills in children with autism. *Iranian Journal of Psychiatry* 12(4):233–237
- Dapretto M, Davies MS, Pfeifer JH, Scott AA, Sigman M, Bookheimer SY, Iacoboni M (2006) Understanding emotions in others: mirror neuron dysfunction in children with autism spectrum disorders. *Nature neuroscience* 9(1):28
- David FJ, Baranek GT, Giuliani CA, Mercer VS, Poe MD, Thorpe DE (2009) A pilot study: Coordination of precision grip in children and adolescents with high functioning autism. *Pediatric Physical Therapy* 21(2):205–211
- Di Martino A, Kelly C, Grzadzinski R, Zuo XN, Mennes M, Mairena MA, Lord C, Castellanos FX, Milham MP (2011) Aberrant striatal functional connectivity in children with autism. *Biological psychiatry* 69(9):847–856
- Dufek JS, Eggleston JD, Harry JR, Hickman RA (2017) A comparative evaluation of gait between children with autism and typically developing matched controls. *Medical Sciences* 5(1), DOI 10.3390/medsci5010001
- Dziuk M, Larson JG, Apostu A, Mahone E, Denckla M, Mostofsky S (2007) Dyspraxia in autism: association with motor, social, and communicative deficits. *Developmental Medicine and Child Neurology* 49(10):734–739
- Fatemi SH, Halt AR, Realmuto G, Earle J, Kist DA, Thuras P, Merz A (2002) Purkinje cell size is reduced in cerebellum of patients with autism. *Cellular and molecular neurobiology* 22(2):171–175
- Foss-Feig JH, Heacock JL, Cascio CJ (2012) Tactile responsiveness patterns and their association with core features in autism spectrum disorders. *Research in*

- autism spectrum disorders 6(1):337–344
- Gallese V, Rochat MJ, Berchio C (2013) The mirror mechanism and its potential role in autism spectrum disorder. *Developmental Medicine & Child Neurology* 55(1):15–22, DOI 10.1111/j.1469-8749.2012.04398.x
- Ghaziuddin M, Butler E (1998) Clumsiness in autism and asperger syndrome: a further report. *Journal of Intellectual Disability Research* 42(1):43–48, DOI 10.1046/j.1365-2788.1998.00065.x
- Glazebrook CM, Elliott D, Lyons J (2006) A kinematic analysis of how young adults with and without autism plan and control goal-directed movements. *Motor control* 10(3):244–264
- Goldman S, Wang C, Salgado MW, Greene PE, Kim M, Rapin I (2009) Motor stereotypies in children with autism and other developmental disorders. *Developmental Medicine and Child Neurology* 51(1):30–38
- Gordon B, Stark S (2007) Procedural learning of a visual sequence in individuals with autism. *Focus on Autism and Other Developmental Disabilities* 22(1):14–22, DOI 10.1177/10883576070220010201
- Greczek J, Kaszubski E, Atrash A, Matarić M (2014) Graded cueing feedback in robot-mediated imitation practice for children with autism spectrum disorders. In: *Robot and Human Interactive Communication, 2014 RO-MAN: The 23rd IEEE International Symposium on, IEEE*, pp 561–566
- Guillot A, Collet C, Nguyen VA, Malouin F, Richards C, Doyon J (2009) Brain activity during visual versus kinesthetic imagery: an fMRI study. *Human brain mapping* 30(7):2157–2172
- Hamilton AFdC, Brindley RM, Frith U (2007) Imitation and action understanding in autistic spectrum disorders: how valid is the hypothesis of a deficit in the mirror neuron system? *Neuropsychologia* 45(8):1859–1868
- Hammes J, Langdell T (1981) Precursors of symbol formation and childhood autism. *Journal of Autism and Developmental Disorders* 11(3):331–346
- Hanaie R, Mohri I, Kagitani-Shimono K, Tachibana M, Azuma J, Matsuzaki J, Watanabe Y, Fujita N, Taniike M (2013) Altered microstructural connectivity of the superior cerebellar peduncle is related to motor dysfunction in children with autistic spectrum disorders. *The Cerebellum* 12(5):645–656, DOI 10.1007/s12311-013-0475-x
- Henderson S, Sugden D (1992) *Movement assessment battery for children*. London, The Psychological Corporation Ltd 62
- Heyes C (2001) Causes and consequences of imitation. *Trends in cognitive sciences* 5(6):253–261
- Higashionna T, Iwanaga R, Tokunaga A, Nakai A, Tanaka K, Nakane H, Tanaka G (2017) Relationship between motor coordination, cognitive abilities, and academic achievement in japanese children with neurodevelopmental disorders. In: *Hong Kong journal of occupational therapy : HKJOT*
- Hilton CL, Zhang Y, Whilte MR, Klohr CL, Constantino J (2012) Motor impairment in sibling pairs concordant and discordant for autism spectrum disorders. *Autism* 16(4):430–441, DOI 10.1177/1362361311423018, PMID: 22013131
- Huijnen CA, Lexis MA, Jansens R, de Witte LP (2016) Mapping robots to therapy and educational objectives for children with autism spectrum disorder. *Journal of autism and developmental disorders* 46(6):2100–2114
- Iacoboni M, Molnar-Szakacs I, Gallese V, Buccino G, Mazziotta JC, Rizzolatti G (2005) Grasping the intentions of others with one’s own mirror neuron system. *PLoS biology* 3(3):e79
- Idei H, Murata S, Chen Y, Yamashita Y, Tani J, Ogata T (2018) A neurorobotics simulation of autistic behavior induced by unusual sensory precision. *Computational Psychiatry* 2:164–182
- Izadi-Najafabadi S, Mirzakhani-Araghi N, Miri-Lavasani N, Nejati V, Pashazadeh-Azari Z (2015) Implicit and explicit motor learning: Application to children with autism spectrum disorder (asd). *Research in developmental disabilities* 47:284–296
- Jamey K, Foster NE, Sharda M, Tuerk C, Nadig A, Hyde KL (2019) Evidence for intact melodic and rhythmic perception in children with autism spectrum disorder. *Research in Autism Spectrum Disorders* 64:1–12, DOI <https://doi.org/10.1016/j.rasd.2018.11.013>
- Jasmin E, Couture M, Mckinley PK, Reid G, Fombonne EJ, Gisel E (2009) Sensori-motor and daily living skills of preschool children with autism spectrum disorders. *Journal of autism and developmental disorders* 39 2:231–41
- Jones CR, Simonoff E, Baird G, Pickles A, Marsden AJ, Tregay J, Happé F, Charman T (2018) The association between theory of mind, executive function, and the symptoms of autism spectrum disorder. *Autism Research* 11(1):95–109
- Kopp S, Beckung E, Gillberg C (2010) Developmental coordination disorder and other motor control problems in girls with autism spectrum disorder and/or attention-deficit/hyperactivity disorder. *Research in developmental disabilities* 31(2):350–361
- Krakauer JW, Shadmehr R (2007) Towards a computational neuropsychology of action. *Progress in brain research* 165:383–394
- Kushki A, Chau T, Anagnostou E (2011) Handwriting difficulties in children with autism spectrum disorder

- ders: A scoping review. *Journal of autism and developmental disorders* 41(12):1706–1716
- LaGasse AB, Hardy MW (2013b) Rhythm, movement, and autism: using rhythmic rehabilitation research as a model for autism. *Frontiers in integrative neuroscience* 7:19
- Larson JCG, Bastian AJ, Donchin O, Shadmehr R, Mostofsky SH (2008) Acquisition of internal models of motor tasks in children with autism. *Brain : a journal of neurology* 131 Pt 11:2894–903
- Lee J, Obinata G, Aoki H (2014) A pilot study of using touch sensing and robotic feedback for children with autism. In: *Proceedings of the 2014 ACM/IEEE international conference on Human-robot interaction*, ACM, pp 222–223
- Lin CW, Lin HY, Lo YC, Chen YJ, Hsu YC, Chen YL, Tseng WYI, Gau SSF (2019) Alterations in white matter microstructure and regional volume are related to motor functions in boys with autism spectrum disorder. *Progress in Neuro-Psychopharmacology and Biological Psychiatry* 90:76 – 83, DOI <https://doi.org/10.1016/j.pnpbp.2018.11.008>
- Luft AR, McCombe-Waller S, Whittall J, Forrester LW, Macko RF, Sorkin JD, Schulz JB, Goldberg AP, Hanley DF (2004) Repetitive bilateral arm training and motor cortex activation in chronic stroke: a randomized controlled trial. *Journal of the American Medical Association (JAMA)* 292 15:1853–61
- MacDonald M, Lord C, Ulrich DA (2014) Motor skills and calibrated autism severity in young children with autism spectrum disorder. *Adapted physical activity quarterly* 31(2):95–105
- Manwaring SS, Mead DL, Swineford L, Thurm A (2017) Modelling gesture use and early language development in autism spectrum disorder. *International Journal of Language & Communication Disorders* 52(5):637–651, DOI 10.1111/1460-6984.12308
- Meltzoff A (1993) The role of imitation in understanding persons and developing theory of mind. *Understanding other minds: Perspectives from autism* pp 335–366
- Ming X, Brimacombe M, Wagner GC (2007) Prevalence of motor impairment in autism spectrum disorders. *Brain and Development* 29(9):565 – 570, DOI <https://doi.org/10.1016/j.braindev.2007.03.002>
- Mizuno A, Villalobos ME, Davies MM, Dahl BC, Müller RA (2006) Partially enhanced thalamocortical functional connectivity in autism. *Brain research* 1104(1):160–174
- Molloy CA, Dietrich KN, Bhattacharya A (2003) Postural stability in children with autism spectrum disorder. *Journal of autism and developmental disorders* 33(6):643–652
- Moorthy RS, Pugazhenth S (2016) Imitation based training to enhance psychomotor skills in autistic children using a snatcher robot. In: *Robotics and Automation for Humanitarian Applications (RAHA), 2016 International Conference on, IEEE*, pp 1–6
- Moorthy RS, Vigneshwaran G, Iyer AR, Pugazhenth S (2016) Mechatronic-shoe kit for training children with asd in enhancement of psychomotor and daily life skills. In: *2016 International Conference on Robotics: Current Trends and Future Challenges (RCTFC), IEEE*, pp 1–6
- Mostofsky SH, Powell SK, Simmonds DJ, Goldberg MC, Caffo B, Pekar JJ (2009) Decreased connectivity and cerebellar activity in autism during motor task performance. *Brain* 132(9):2413–2425
- Nair A, Treiber J, Shukla DK, Shih P, Müller RA (2013) Impaired thalamocortical connectivity in autism spectrum disorder: a study of functional and anatomical connectivity. *Brain : a journal of neurology* 136 Pt 6:1942–55
- Nair A, Carper RA, Abbott AE, Chen CP, Solders S, Nakutin S, Datko MC, Fishman I, Müller RA (2015) Regional specificity of aberrant thalamocortical connectivity in autism. *Human Brain Mapping* 36(11):4497–4511, DOI 10.1002/hbm.22938
- Nazarali N, Glazebrook CM, Elliott D (2009) Movement planning and reprogramming in individuals with autism. *Journal of Autism and Developmental Disorders* 39(10):1401–1411
- Nemeth D, Janacsek K, Balogh V, Londe Z, Mingesz R, Fazekas M, Jambori S, Danyi I, Vetro A (2010) Learning in autism: implicitly superb. *PloS one* 5(7):e11731
- Nishitani N, Avikainen S, Hari R (2004) Abnormal imitation-related cortical activation sequences in asperger’s syndrome. *Annals of neurology* 55(4):558–562
- Oberman LM, Ramachandran VS (2007) The simulating social mind: the role of the mirror neuron system and simulation in the social and communicative deficits of autism spectrum disorders. *Psychological bulletin* 133(2):310
- Oldehinkel M, Mennes M, Marquand A, Charman T, Tillmann J, Ecker C, Dell’Acqua F, Brandeis D, Banaschewski T, Baumeister S, Moessnang C, Baron-Cohen S, Holt R, Bölte S, Durston S, Kundu P, Lombardo MV, Spooren W, Loth E, Murphy DG, Beckmann CF, Buitelaar JK, Ahmad J, Ambrosino S, Auyeung B, Banaschewski T, Baron-Cohen S, Baumeister S, Beckmann CF, Bölte S, Bourgeron T, Bours C, Brammer M, Brandeis D, Brogna C, de Bruijn Y, Buitelaar JK, Chakrabarti B, Char-

- man T, Cornelissen I, Crawley D, Dell'Acqua F, Dumas G, Durston S, Ecker C, Faulkner J, Frouin V, Garcés P, Goyard D, Ham L, Hayward H, Hipp J, Holt R, Johnson MH, Jones EJ, Kundu P, Lai MC, D'ardhuy XL, Lombardo MV, Loth E, Lythgoe DJ, Mandl R, Marquand A, Mason L, Mennes M, Meyer-Lindenberg A, Moessnang C, Mueller N, Murphy DG, Oakley B, O'Dwyer L, Oldehinkel M, Oranje B, Pandina G, Persico AM, Ruggieri B, Ruigrok A, Sabet J, Sacco R, Cáceres ASJ, Simonoff E, Spooren W, Tillmann J, Toro R, Tost H, Waldman J, Williams SC, Wooldridge C, Zwiers MP (2018) Altered connectivity between cerebellum, visual, and sensory-motor networks in autism spectrum disorder: Results from the eu-aims longitudinal european autism project. *Biological Psychiatry: Cognitive Neuroscience and Neuroimaging* DOI <https://doi.org/10.1016/j.bpsc.2018.11.010>
- Palsbo SE, Hood-Szivek P (2012) Effect of robotic-assisted three-dimensional repetitive motion to improve hand motor function and control in children with handwriting deficits: a nonrandomized phase 2 device trial. *American Journal of Occupational Therapy* 66(6):682–690
- Peña de Moraes ÍA, Massetti T, Brusque Crocetta T, Dias da Silva T, Del Ciello de Menezes L, Bandeira de Mello Monteiro C, Magalhães FH (2017) Motor learning characterization in people with autism spectrum disorder. *Dementia and Neuropsychologia* 11(3)
- Pierno AC, Mari M, Lusher D, Castiello U (2008) Robotic movement elicits visuomotor priming in children with autism. *Neuropsychologia* 46(2):448–454
- Press C, Richardson D, Bird G (2010) Intact imitation of emotional facial actions in autism spectrum conditions. *Neuropsychologia* 48(11):3291–3297
- Provost B, Lopez BR, Heimerl S (2007) A comparison of motor delays in young children: autism spectrum disorder, developmental delay, and developmental concerns. *Journal of autism and developmental disorders* 37(2):321–328
- Purpura G, Fulceri F, Puglisi V, Masoni P, Contaldo A (2016) Motor coordination impairment in children with autism spectrum disorder: a pilot study using movement assessment battery for children-2 checklist. *Minerva Pediatrica*
- Rinehart NJ, Tonge BJ, Bradshaw JL, Ianseck R, Enticott PG, McGinley J (2006a) Gait function in high-functioning autism and asperger's disorder. *European child & adolescent psychiatry* 15(5):256–264
- Rinehart NJ, Tonge BJ, Ianseck R, McGinley J, Brereton AV, Enticott PG, Bradshaw JL (2006b) Gait function in newly diagnosed children with autism: cerebellar and basal ganglia related motor disorder. *Developmental medicine and child neurology* 48(10):819–824
- Riquelme I, Hatem S, Montoya P (2016) Abnormal pressure pain, touch sensitivity, proprioception, and manual dexterity in children with autism spectrum disorders. *Neural Plasticity* 2016(1723401):1–9
- Ritvo ER, Freeman B, Scheibel AB, Duong T, Robinson H, Guthrie D, Ritvo A (1986) Lower purkinje cell counts in the cerebella of four autistic subjects: Initial findings of the ucla-nsac research report. *The American journal of psychiatry*
- Rizzolatti G, Craighero L (2004) The mirror-neuron system. *Annu Rev Neurosci* 27:169–192
- Robins B, Dautenhahn K (2014) Tactile interactions with a humanoid robot: novel play scenario implementations with children with autism. *International journal of social robotics* 6(3):397–415
- Rodgers RA, Travers BG, Mason AH (2019) Bimanual reach to grasp movements in youth with and without autism spectrum disorder. *Frontiers in Psychology* 9:2720, DOI 10.3389/fpsyg.2018.02720
- Rogers SJ, Pennington BF (1991) A theoretical approach to the deficits in infantile autism. *Development and psychopathology* 3(2):137–162
- Rogers SJ, Young GS, Cook I, Giolzetti A, Ozonoff S (2010b) Imitating actions on objects in early-onset and regressive autism: Effects and implications of task characteristics on performance. *Development and Psychopathology* 22(1):71–85
- Romero V, Fitzpatrick P, Schmidt R, Richardson MJ (2016) Using cross-recurrence quantification analysis to understand social motor coordination in children with autism spectrum disorder. In: *Recurrence Plots and Their Quantifications: Expanding Horizons*, Springer, pp 227–240
- Sacrely LA, Germani T, Bryson S, Zwaigenbaum L (2014) Reaching and grasping in autism spectrum disorder: A review of recent literature. *Frontiers in Neurology* 5:6, DOI 10.3389/fneur.2014.00006
- Salowitz NM, Eccarius P, Karst J, Carson A, Schohl K, Stevens S, Van Hecke AV, Scheidt RA (2013) Brief report: visuo-spatial guidance of movement during gesture imitation and mirror drawing in children with autism spectrum disorders. *Journal of autism and developmental disorders* 43(4):985–995
- Schipul SE, Keller TA, Just MA (2011) Inter-regional brain communication and its disturbance in autism. In: *Frontiers in Systems Neuroscience*
- Schopler E (2005) *Psychoeducational Profile: PEP-3; TEACCH Individualized Psychoeducational Assessment for Children with Autism Spectrum Disorders*. Pro-ed

- Sivaswamy L, Kumar A, Rajan D, Behen M, Muzik O, Chugani D, Chugani H (2010) A diffusion tensor imaging study of the cerebellar pathways in children with autism spectrum disorder. *Journal of Child Neurology* 25(10):1223–1231, DOI 10.1177/0883073809358765, pMID: 20179000
- So WC, Wong MKY, Lam WY, Cheng CH, Yang JH, Huang Y, Ng P, Wong WL, Ho CL, Yeung KL, et al. (2018) Robot-based intervention may reduce delay in the production of intransitive gestures in chinese-speaking preschoolers with autism spectrum disorder. *Molecular autism* 9(1):34
- So WC, Wong MKY, Lam WY, Cheng CH, Ku SY, Lam KY, Huang Y, Wong WL (2019) Who is a better teacher for children with autism? comparison of learning outcomes between robot-based and human-based interventions in gestural production and recognition. *Research in developmental disabilities* 86:62–75
- Southgate V, Hamilton AFdC (2008) Unbroken mirrors: Challenging a theory of autism. *Trends in cognitive sciences* 12(6):225–229
- Sowden S, Koehne S, Catmur C, Dziobek I, Bird G (2016) Intact automatic imitation and typical spatial compatibility in autism spectrum disorder: Challenging the broken mirror theory. *Autism Research* 9(2):292–300
- Srinivasan SM, Kaur M, Park IK, Gifford TD, Marsh KL, Bhat AN (2015a) The effects of rhythm and robotic interventions on the imitation/praxis, interpersonal synchrony, and motor performance of children with autism spectrum disorder (asd): a pilot randomized controlled trial. *Autism research and treatment* 2015
- Stoit AM, van Schie HT, Slaats-Willemse DI, Buitelaar JK (2013) Grasping motor impairments in autism: not action planning but movement execution is deficient. *Journal of autism and developmental disorders* 43(12):2793–2806
- Traynor J, Doyle-Thomas K, Hanford L, Foster N, Tryfon A, Hyde K, Anagnostou E, Evans A, Zwaigenbaum L, Hall G, et al. (2018) Indices of repetitive behaviour are correlated with patterns of intrinsic functional connectivity in youth with autism spectrum disorder. *Brain research* 1685:79–90
- Tryfon A, Foster NE, Ouimet T, Doyle-Thomas K, Anagnostou E, Sharda M, Hyde KL (2017) Auditory-motor rhythm synchronization in children with autism spectrum disorder. *Research in Autism Spectrum Disorders* 35:51 – 61, DOI <https://doi.org/10.1016/j.rasd.2016.12.004>
- Turner KC, Frost L, Linsenbardt D, McIlroy JR, Müller RA (2006) Atypically diffuse functional connectivity between caudate nuclei and cerebral cortex in autism. *Behavioral and Brain Functions* 2(1):34
- Vanvuchelen M, Roeyers H, De Weerd W (2011) Do imitation problems reflect a core characteristic in autism? evidence from a literature review. *Research in Autism Spectrum Disorders* 5(1):89–95
- Vernazza-Martin S, Martin N, Vernazza A, Lepellec-Muller A, Rufo M, Massion J, Assaiante C (2005) Goal directed locomotion and balance control in autistic children. *Journal of autism and developmental disorders* 35(1):91–102
- Villalobos ME, Mizuno A, Dahl BC, Kemmotsu N, Müller RA (2005) Reduced functional connectivity between v1 and inferior frontal cortex associated with visuomotor performance in autism. *Neuroimage* 25(3):916–925
- Vivanti G, McCormick C, Young GS, Abucayan F, Hatt N, Nadig A, Ozonoff S, Rogers SJ (2011) Intact and impaired mechanisms of action understanding in autism. *Developmental psychology* 47(3):841
- Vivanti G, Trembath D, Dissanayake C (2014) Mechanisms of imitation impairment in autism spectrum disorder. *Journal of Abnormal Child Psychology* 42(8):1395–1405
- Williams RS, Hauser SL, Purpura DP, DeLong GR, Swisher CN (1980) Autism and mental retardation: neuropathologic studies performed in four retarded persons with autistic behavior. *Archives of neurology* 37(12):749–753
- Xavier J, Bursztejn C, Stiskin M, Canitano R, Cohen D (2015) Autism spectrum disorders: An historical synthesis and a multidimensional assessment toward a tailored therapeutic program. *Research in Autism Spectrum Disorders* 18:21–33
- Xavier J, Gauthier S, Cohen D, Zahoui M, Chetouani M, Villa F, Berthoz A, Anzalone S (2018) Interpersonal synchronization, motor coordination, and control are impaired during a dynamic imitation task in children with autism spectrum disorder. *Frontiers in Psychology* 9:1467, DOI 10.3389/fpsyg.2018.01467
- Zheng Z, Young EM, Swanson AR, Weitlauf AS, Warren ZE, Sarkar N (2016) Robot-mediated imitation skill training for children with autism. *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 24(6):682–691