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ORIGINAL RESEARCH

Effect of Robot–Child Interactions on Bilateral Coordination Skills of Typically Developing Children and a Child With Autism Spectrum Disorder: A Preliminary Study

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***Background*:** Coordination develops gradually over development with younger children showing more unstable coordination patterns compared to older children and adults. In addition, children with Autism Spectrum Disorders (ASDs) display significant coordination impairments. In the current study, we examined whether robot–child interactions could improve bilateral coordination skills of typically developing (TD) children and one child with ASD. ***Method*:** Fourteen TD children between four and seven years of age and an 11-year-old child with ASD performed dual-limb and multilimb actions within a solo and social context during a pre- and posttest. Between the pre- and posttests, eight training sessions were offered across four weeks during a robot imitation context involving karate and dance actions. ***Results*:** Younger TD children and the child with ASD improved their solo coordination whereas the older TD children increased their social coordination. ***Limitations*:** This preliminary study lacked a control group. ***Conclusions*:** Robot–child interactions may facilitate bilateral coordination and could be a promising intervention tool for children with ASDs.

***Keywords*:** motor, coordination, dual-limb, multilimb, social

The rapid advancements in the field of socially assistive robotics have made it possible for social robots to interact with humans (Dautenhahn & Werry, 2004; Scassellati, Admoni, & Mataric, 2012). Socially assistive robots are electro-mechanical machines capable of interacting with and helping humans (Dautenhahn & Werry, 2004; Scassellati et al., 2012). Social robot design could vary from animal forms (pet-like) to humanoid forms (with human features) with a range of motor and communication capabilities (Dautenhahn & Werry, 2004; Scassellati et al., 2012). Some case studies report that humanoid robots facilitate imitation skills and social interactions in children with autism (Robins, Dautenhahn, te Boekhorst, & Billiard, 2004; Scassellati et al., 2012). However, the broader empirical evidence for the use of humanoid robots in children with autism or typically developing (TD) children is clearly lacking (Diehl, Schmitt, Villano, & Crowell, 2011). Researchers have assumed that children with autism find humanoid robots more engaging and less intimidating than humans due to their social simplicity (Dautenhahn & Werry, 2004; Scassellati et al., 2012). This argument cannot be made when there are practically no studies on interactions between humanoid robots and TD children. Moreover, only one study has reported on how robots promote motor skills such as reaching in children with autism and TD children (Pierno, Mari, Lusher, & Castiello, 2008). Hence, the broad aim of this research was to examine whether robot–child interactions improved motor coordination of younger and older TD children. In addition, we extended this work to one child with Autism Spectrum Disorders (ASDs) so that these data served as a foundation for larger future studies in children with ASDs.

School-age children change their coordination abilities between 4–10 years of age with more consistent and less variable dual-limb (using two limbs) and ipsilateral coordination (using two homologous limbs) emerging earlier in life compared with the more complex multilimb (using four limbs) and contralateral coordination (using two heterologous limbs). Children from 4–10 years of age show stable and consistent performance during simpler dual-limb actions of clapping only or walking only, whereas complex multilimb actions such

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as “clapping and walking” become more synchronized with increasing age (Getchell, 2006). In terms of bilateral coordination, ipsilateral (same-sided) or contralateral (opposite-sided) hand-foot movements are unstable until six years of age and improve between 7–10 years of age (Volman, Laroy, & Jongmans, 2006). Taken together, in spite of contextual and task-related constraints, there are clear developmental trajectories of multilimb, bilateral coordination in school-age children.

Coordination in a social context has added constraints of perceiving the motions of a social partner and acting with them (Marsh, Richardson, & Schmidt, 2009). Coordination within a social context or the ability to move with others appears to improve across development. In a recent study, adult–adult pairs showed better synchronization of bilateral drumming actions compared to older child–child pairs who in turn performed better than younger child–child pairs (Kleinspehn-Ammerlahn, Riediger, Schmiedek, von Oertzen, Li, & Lindenberger, 2011). However, no study has compared solo and social coordination in TD children across various coordination patterns of dual-limb and multilimb, bilateral actions. Therefore, the two aims of this project were 1) to examine the effects of robot–child interactions on dual and multilimb, bilateral coordination of younger and older TD children; and 2) to compare coordination across solo and social contexts in younger and older TD children. We hypothesized that a) both groups of children will improve their multilimb bilateral coordination following training and b) bilateral coordination in the social context will be poor compared with the solo context for the younger TD children. Lastly, we hypothesized that the high-functioning child with ASD would show improvements in multilimb, bilateral coordination following training, and his bilateral coordination in the social context will be lower compared to the solo context.

Method

Participants

Fourteen TD children between the ages of 4–7 years participated in the study. Seven children were in the younger age group of 4–5.5 years (Mean±SE 4.91 ± 0.23, 5 males and 2 females) and seven children were in the older age group of 5.5–7 years (Mean±SE 6.98 ± 0.25, 4 males and 3 females). In addition, we observed one 11-year-old, high-functioning male child diagnosed with ASD. We confirmed the diagnosis of Asperger syndrome through medical and school records based on a full neuropsychological evaluation, which included the Autism Diagnostic Observation Schedule (ADOS), a diagnostic tool for autism (Lord, Rutter, DiLavore, & Risi, 1999). Children were admitted in the study following parental consent approved by the University of Connecticut’s Institutional Review Board.

Procedures

The study was conducted over six weeks with the first and last week reserved for a pretest and a posttest session. Training was provided in the four weeks between the tests. The pretest included a standardized test of bilateral coordination using the Bruininks-Oseretsky Test of Motor Proficiency (BOTMP) and kinematic analysis of two bilateral test actions that were dual-limb and multilimb in nature. The kinematic analysis of the bilateral test actions was repeated as a posttest.

Testing Measures

The BOTMP is a standardized and normed test of overall motor performance with multiple subtests and a short-form (SF) version. The BOTMP-SF was used to confirm typical motor development during the pretest. In addition, we used the Bilateral Coordination (BC) subtest of the BOTMP to assess the levels of bilateral coordination. The BOTMP-SF percentile scores for both groups were in the typical range (Younger TD children = 84.29 ± 18.23, Older TD children = 74.71 ± 12.34) whereas the child with ASD was in 14th percentile, which was a significant developmental delay. As expected, the overall motor performance of the older TD children was better than the younger TD children based on the BOTMP-SF (Raw scores: Younger TD children = 43.71 ± 6.99 vs. Older TD children = 62 ± 4.83, $p < .01$ from a paired t test). In terms of bilateral coordination, older TD children (17 ± 1.27) had higher BC subtest scores compared with the younger TD children (13.14 ± 1.06, $p = .03$ from a paired t test) and the 11-year-old child with ASD performed at the level of a 7-year-old with a BC subtest score of 16.

During the kinematic analysis, each child was observed during two general test actions not practiced during the training sessions: a simple, symmetrical dual-limb and a more complex, contralateral multilimb action during the pretest and the posttest. The symmetrical dual-limb action involved bilaterally symmetrical up and down shaking of two maracas. The contralateral multilimb action involved shaking of two maracas while marching. Specifically, each child lifted one leg and the opposite arm and then the pattern reversed. Both actions were done in a solo (moving on your own) and a social (moving with an adult partner) context. The motions of the adult partner were consistent because the adult followed a steady metronome beat of 80 beats per minute, audible to the adult only. A four-sensor Polhemus electromagnetic system captured position data from both hands and feet at a sampling rate of 240 Hz. Hand markers were placed at the base of the index finger of each hand. Foot markers were placed at the head of the first metatarsal of each foot. Each trial comprised of 20–30 seconds of data or an average of 12.98 ± 0.40 movement cycles for dual-limb actions and 11.87 ± 0.57 movement cycles for multilimb actions. Each time series was filtered using a Butterworth filter with a cut-off of 5 Hz.

Training Protocol

Each child received eight sessions of robot-adult-child interactions across four weeks (i.e., two sessions/week). Each session lasted about 30 min and involved an imitation game between the child and a 7-inch tall humanoid robot called Isobot (Tomy, Inc., see Figure 1A). An adult trainer controlled the robot using an infrared sensor and a custom-built, laptop-based robot controlling software (see Figure 1B). Each session involved three conditions. In the baseline condition (2 min), the Isobot greeted the child with a bow or danced to music. Children mainly observed the robot and did not imitate the robot spontaneously. In the robot-led condition (12–14 min), we encouraged action imitation. The Isobot performed preprogrammed actions based on a karate or dance theme and the child was instructed to copy the robot. A total of five actions were included within each session. A verbal label, such a "backhand" or a "roundhouse kick," was assigned to each action. If the child appeared to clearly miss out on certain components of the action, the trainer would ask the child to hone into the robot's certain body segments. We promoted practice, discovery learning without explicit feedback on the form of actions, and a visual reference was provided by the robot's actions. Of the 40 training actions, 73% were bilaterally asymmetrical, 75% were multilimb, 87% were multistep, and 60% were vertical or multiplanar in nature. In the child-led condition (8–10 min), we facilitated action recall. The trainer asked the child to remember and demonstrate the actions he/she just learned so that the robot could copy him/her (see Figure 1B). In terms of feedback, first we offered a listing of action labels then we offered other verbal cues to describe the features of the action such as limbs used. At the end of each demonstration, the trainer triggered the robot to perform the appropriate action.

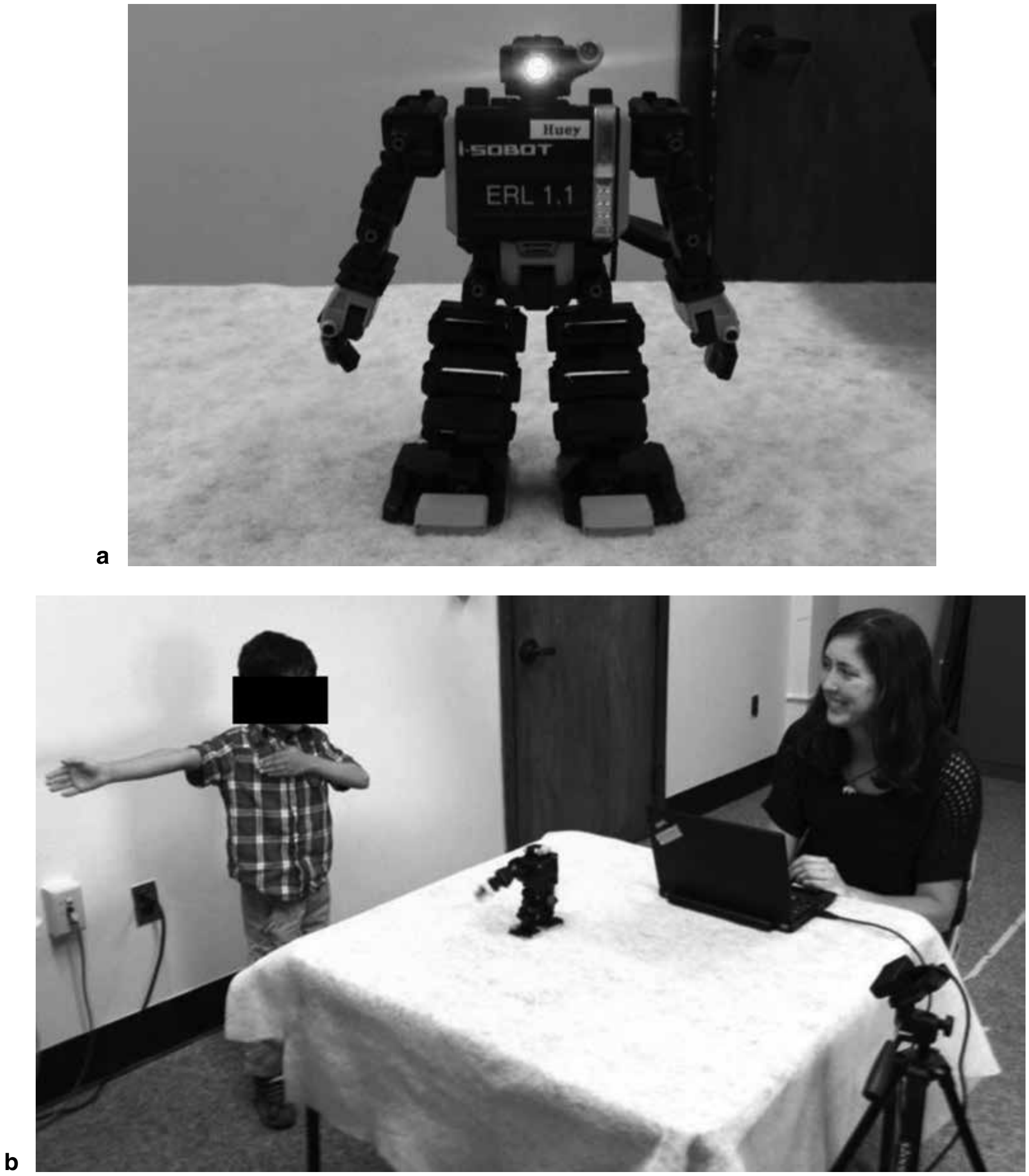


Figure 1 — (a) Isobot and (b) training set up.

Data Analysis

Continuous Relative Phase (CRP) analysis is a tool used to examine coordination between segments (Marsh et al., 2009). It was used to analyze training-related changes (pretest vs. posttest) and context-related differences (solo vs. social) for the two test actions. In CRP analysis, relative phase is defined as the difference in phase between two moving segments (s) (i.e., θ_{s1}–θ_{s2}). Phase or θ of a moving segment is defined as $\tan^{-1}[(dX_s/dt)/X_s]$, where dX_s/dt = instantaneous velocity of the moving segment "s" and X_s = rescaled position of the moving segment "s." CRP values at each point in time could range from 0°–180° with the majority of the data within the task-appropriate range. For example, during in-phase motions the highest amount of data would lie in the 0°–20° range followed by 20°–40° and the 40°–60° range and so on (Scholz & Kelso, 1989). Data were examined at narrower bin ranges of 0°–20° and broader bins of 0°–60° and the broader bin ranges were considered appropriate because it accommodated the variability observed in the younger TD children. As a result, the CRP values per trial were grouped into three bins: 0°–60°, 60°–120°, and 120°–180°. Symmetrical or in-phase movements ranged from 0°–60°, opposite or antiphase movements ranged from 120°–180° and out-of-phase or off-sync motions ranged from 60°–120°. For the symmetrical dual-limb action, the relative phase between the two hands was calculated. For the contralateral multilimb action, the relative phase between one hand and the opposite foot was calculated. For both actions, we expected the majority of the data to lie in the 0°–60° range and this range was referred to as the "task-appropriate CRP bin." For each test action, the percent time spent in the task-appropriate CRP bin was calculated. Lastly, Wilcoxon's nonparametric tests were done for group comparisons of CRP data due to small sample size ($n = 7$). Statistical significance was set at $p < .05$ and p-values between 0.05–0.1 were considered a statistical trend. Individual changes were also examined in all TD children and the child with ASD.

Results

Changes in Bilateral Coordination Between the Pre- and Posttest

The Wilcoxon's nonparametric tests revealed that both younger and older TD children spent greater time in the task-appropriate CRP bin for the contralateral multilimb action during the posttest compared with the pretest. For the younger TD children, the percent time spent in the task-appropriate CRP bin was greater in the posttest (56.44 ± 5.73) compared with pretest (43.74 ± 4.66; $Z = -2.366$, $p = .02$, see Figure 2A) for the solo context. For the older TD children, percent time spent in the task-appropriate CRP bin was greater in the posttest (53.84 ± 3.60) compared with the pretest (42.51 ± 6.11; $Z = -2.197$, $p = .03$, see Figure 2A) for the social context. In terms of individual data, six to seven younger and older TD children followed the group's significant trend. No training-related changes were observed during the symmetrical dual-limb action in both groups due to their ceiling level performance in the pretest. For the child with ASD, training-related improvements differed across the solo and social contexts. During the solo context, the percent time spent in the task-appropriate CRP bin increased with training for the contralateral multilimb action (pretest = 55.50, posttest = 81.10, see Figure 2A). During the social context, the percent time spent in the task-appropriate CRP bin increased with training for the symmetrical dual-limb action (pretest = 58.90, posttest = 98.20) and decreased with training for the contralateral multilimb action (pretest = 42.10, posttest = 18.20).

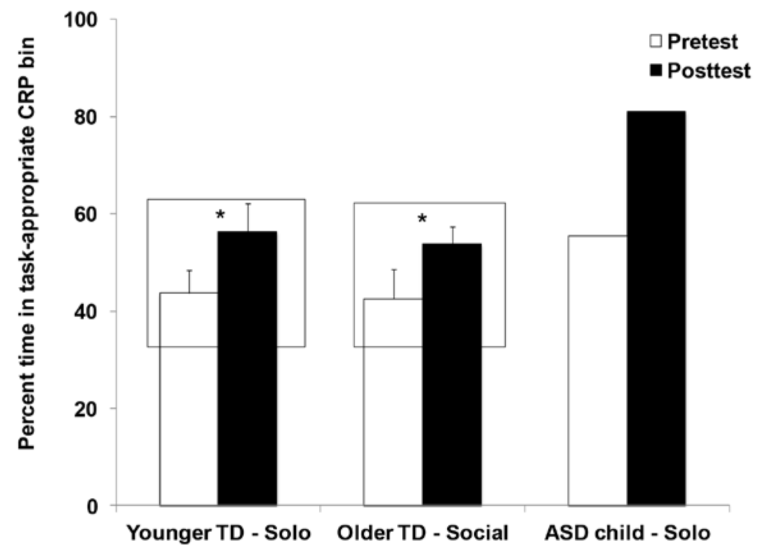
Differences in Bilateral Coordination Between Solo and Social Contexts

The Wilcoxon's nonparametric tests revealed a statistical trend in younger TD children. Younger TD children spent greater time in the task-appropriate CRP bin for the solo context (50.09 ± 3.96) compared with the social context (38.72 ± 4.41, $Z = -1.85$, $p = .06$) during the multilimb action (see Figure 2B). However, they showed no differences for the dual-limb action across the solo and social contexts. In terms of individual data, five out of seven children followed the younger group's statistical trend. The older TD children showed no differences between solo and social coordination for both test actions. The child with ASD displayed greater coordination in the solo context compared with the social context for both, asymmetrical dual-limb action (solo = 97.80 > social= 78.55) and contralateral multilimb action (solo = 68.30 > social = 30.15; see Figure 2B). In addition, his multilimb coordination was lower than dual-limb coordination.

Discussion

This study was a proof-of-concept for the effects of robot–child interactions on the bilateral coordination skills of TD children and one child with ASD. TD children as well as the child with ASD found the context engaging and were motivated to interact with Isobot. In terms of developmental differences, the older TD children had better bilateral coordination compared with the younger TD children whereas the child with ASD had substantially poor bilateral coordination, equivalent to that of a 7-year-old TD child. In terms of training effects, both TD children as well as the child with ASD showed greater task-appropriate coordination in the posttest compared with the pretest for the complex contralateral multilimb action (Figure 2A). In terms of solo vs. social differences, younger TD children and the child with ASD had poor multilimb coordination during the social context compared with the solo context (Figure 2B).

Younger and older TD children, and the child with ASD improved coordination during the contralateral, multilimb action following training (see Figure 2A).


2A: Changes in multilimb coordination following training

2B: Differences in solo and social coordination

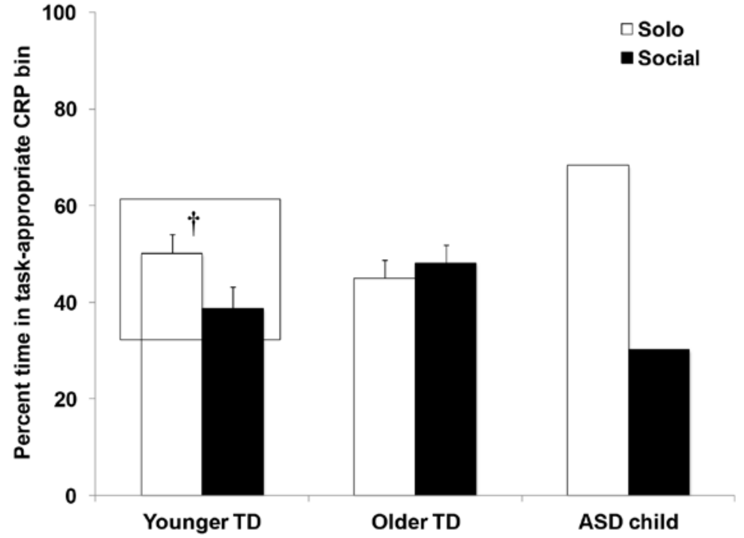


Figure 2 — (A) Changes in CRP for the multilimb action between pre- and posttest, and (B) differences in CRP for multilimb, solo, and social actions in the younger and older typically developing children and one child with Autism Spectrum Disorder. * indicates *p*-value < 0.05 and † indicates a *p*-value between 0.05–0.1.

While the training-related improvements in the younger TD children and the child with ASD were limited to the solo context, the older TD children improved their multilimb coordination in the social context. These context-specific, training-related changes in the younger and older TD children could be attributed to the experiences they received during robot–child interactions: a) the practice of performing multilimb, bilaterally symmetrical actions and b) the social monitoring and synchronization with Isobot. Lack of improvements in the social context for the younger TD children may be attributed to their difficulties in monitoring social information or scaling/matching their motions to the adult's movements (Marsh et al., 2009). TD children showed less in-phase coordination with their caregivers compared with adult–adult pairs during a synchronous rocking chair task (Marsh et al., 2009). However, older TD children may have enhanced social monitoring and synchronization abilities. For instance, pairs of older children engaged in social drumming were more synchronous in their drumming patterns compared with pairs of younger children (Kleinspehn-Ammerlahn et al., 2011).

The 11-year-old child with ASD had poor bilateral coordination with performance at the level of a 7-year-old child and an overall motor performance in the 14th percentile as well as poor performance during multiple bilateral test actions. Children with ASDs, including those who are high functioning, often demonstrate significant impairments in motor coordination including poor upper-limb coordination during visuomotor and manual dexterity tasks as well as lower-limb coordination during activities requiring balance and coordination (Bhat, Landa, & Galloway, 2011; Green et al., 2009; Mostofsky et al., 2006). In terms of training-related changes within the solo context, the child with ASD significantly improved his multilimb coordination; which was consistent with the asymmetrical multilimb actions practiced during the robot–child interactions. Within the social context, the child with ASD significantly improved his dual-limb but not multilimb coordination. The training duration was perhaps not adequate for the child with ASD or we cannot assume that practice during robotic interactions will always extend to enhanced social coordination with people.

Only younger TD children reduced their multilimb coordination during the social context compared with the solo context (see Figure 2B). Social coordination relies on the ability to perceive and act on the visual information available from the coactor (Marsh et al., 2009). Young and older TD children differ in their abilities to use visual information while performing bimanual actions (Lantero & Ringenbach, 2007). During a continuous bimanual task, 4- to 5-year-old children relied on proprioceptive feedback versus 8-year-old-children relied on both, visual and proprioceptive information to change their movements (Lantero & Ringenbach, 2007). In our study, we noticed that younger TD children would begin by observing the adult's motions and often shift to observing their own motions instead of focusing on the adult, which may have contributed to their poor performance in the social context. On the other hand, older TD children are better able to modify their movements according to the visual information available from a coactor; thus they may have performed comparably in the solo and the social contexts (Kleinspehn-Ammerlahn et al., 2011). Both groups did not show context-related differences for the dual-limb action due to its task simplicity. Taken together, the differences in solo and social coordination may interact with movement complexity and may differ until the movement pattern is mastered.

The child with ASD showed a major reduction in task-appropriate coordination during the social context compared to solo contexts for both actions—dual and multilimb suggesting that socially embedded actions may be more difficult for children with ASDs. Moreover, his multilimb coordination was worse compared with dual-limb coordination within the social context. These findings fit with what is known about deficits in social monitoring, visuo-motor coordination, and praxis abilities of children with ASDs. Children with ASDs have poor social monitoring (Gernsbacher, Stevenson, Khandakar, & Hill-Goldsmith, 2008) and poor imitation skills, which affect their ability to engage in socially cooperative actions (Colombi et al.; 2009). In addition, as mentioned earlier, children with ASDs have significant coordination deficits during a range of upper and lower-extremity actions (Green et al., 2009). Lastly, children with ASDs have significant difficulties with motor planning of complex actions (Mostofsky et al., 2006), which may contribute to their difficulties in mastering multilimb actions.

Conclusions and Limitations

Our preliminary study is limited by a small sample size, a short period of training, and by the lack of a control group. This study was a proof-of-concept for robot–child interaction effects in TD children with an extension to one child with ASD. Our data suggest that robot–child interactions may facilitate motor practice of multilimb actions leading to greater bilateral coordination and/or social monitoring in TD children and a child with ASD. Currently, we are conducting a randomized controlled trial in children with ASDs using multiple robots with varying motor repertoires, an extended training protocol, and a control group to further validate our preliminary findings. Overall, socially embedded motor activities using robots might be a valuable context for promoting social coordination in children who have social and motor impairments, such as children with ASDs.

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