Early Motor Function of Children With Autism Spectrum Disorder: A Systematic Review

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abstract

CONTEXT: Early motor impairments have been reported in children with neurodevelopmental disorders (NDD), but it is not clear if early detection of motor impairments can identify children at risk for NDD or how early such impairments might be detected.

OBJECTIVE: To characterize early motor function in children later diagnosed with NDD relative to typically developing children or normative data.

DATA SOURCES: The Cumulative Index to Nursing and Allied Health Literature, Embase, Medline, PsycINFO, and Scopus electronic databases were searched.

STUDY SELECTION: Eligible studies were required to include an examination of motor function in children (0–24 months) with later diagnosis of NDD by using standardized assessment tools.

DATA EXTRACTION: Data were extracted by 4 independent researchers. The quality of the studies was assessed by using the Standard Quality Assessment Criteria for Evaluating Primary Research Papers from a Variety of Fields checklist.

RESULTS: Twenty-five studies were included in this review; in most of the studies, the authors examined children with later autism spectrum disorder (ASD). Early motor impairments were detected in children later diagnosed with ASD. The meta-analysis results indicated that differences in fine, gross, and generalized motor functions between the later ASD and typically developing groups increased with age. Motor function across different NDD groups was found to be mixed.

LIMITATIONS: Results may not be applicable to children with different types of NDD not reported in this review.

CONCLUSIONS: Early motor impairments are evident in children later diagnosed with ASD. More research is needed to ascertain the clinical utility of motor impairment detection as an early transdiagnostic marker of NDD risk.

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Neurodevelopmental disorders (NDD) result from a deviation in the development of the brain early in life.[1] According to the *International Classification of Diseases, 11th Revision* (*ICD-11*),[2] NDD include intellectual disability, language or speech disorder, autism spectrum disorder (ASD), learning disorder, developmental coordination disorder (DCD), attention-deficit/hyperactivity disorder (ADHD), and neurodevelopmental syndrome due to prenatal alcohol exposure (a condition also classified under fetal alcohol syndrome in the *ICD-11* and grouped elsewhere under the umbrella term of fetal alcohol spectrum disorder [FASD]).[2] Although these disorders have different etiologies (ie, FASD is clearly linked to alcohol exposure in utero, whereas the origins of the other disorders are less clear), they have substantial comorbidity and overlapping symptoms. For example, individuals with NDD experience significant impairments in an array of neurodevelopmental domains, including cognition, social, and motor functioning. These impairments can have a profound and lifelong impact on health outcomes and quality of life.[3–6]

Early identification of children with NDD facilitates the delivery of support to prevent or minimize later functional impairments.[7] In several studies,[8,9] researchers have discussed the benefits of early intervention (ie, from birth) to capitalize on heightened neuroplasticity and potentially alter developmental outcomes for children at risk.[10–12] However, many children miss the opportunity for any early intervention because a formal diagnosis is not obtained until they reach school age.[13–15] This is partly because NDD diagnosis is frequently contingent on evidence of clinically significant behaviors that typically appear at an older age.[16,17] There is a need to identify early markers of NDD risk that can be used to support referral for preemptive intervention (ie, intervention administered before the full clinical presentation of a disorder).

One early behavioral marker that may serve to identify those who are likely to be later diagnosed with NDD is motor impairment. Although impaired motor development has been investigated primarily and extensively in preterm infants and those at risk for cerebral palsy,[18,19] there is evidence to indicate that early motor impairments may represent a transdiagnostic marker of neurodevelopmental vulnerability. For example, in a recent review, authors reported a high occurrence of abnormal general movements (ie, spontaneous movements present in the first few months of life) in infants later diagnosed with ASD.[20] In another study, it was found that 70% (21 of 30) of children who demonstrated motor delays before 2 years of age fulfilled the diagnostic criteria for NDD at follow-up (between 9 and 98 months).[21] These studies suggest that early motor impairments may prove useful in detecting children at risk for NDD beyond those disorders in which motor dysfunction is a core symptom.

The transdiagnostic or cross-syndrome approach to NDD is focused on the identification of shared characteristics and mechanisms across NDD and interventions that are pertinent across disorders.[16] Although evidence of motor impairments among school-aged children with different NDD is reported elsewhere,[22,23] there has been no synthesis of early motor function across studies of children later diagnosed with different NDD between the ages of 0 and 24 months. Accordingly, our aim for this systematic review was to synthesize studies describing early motor function of children (0–24 months) later diagnosed with NDD by using a transdiagnostic approach. We sought to include studies of children later diagnosed with intellectual disability, language or speech disorder, ASD, learning disorder, DCD, ADHD, and FASD. FASD is an umbrella term that encompasses neurodevelopmental syndrome due to prenatal alcohol exposure (*ICD-11*) and is used in this review because of current and historical inconsistencies in diagnostic terms for NDD associated with prenatal alcohol exposure.

METHODS

In this systematic review, we follow the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines,[24] and the study protocol was registered with PROSPERO (registration number: CRD42019131708).

Eligibility Criteria

Articles were included in the systematic review if (1) the cohort of interest was children with NDD, as identified in the *ICD-11*[2]; (2) they included a comparator group, including typically developing (TD) children or normative data; (3) children were tested for motor function between 0 and 24 months of age; (4) motor functions were assessed by using standardized assessments; and (5) they were published in English peer-reviewed journals. Articles were excluded if the cohort included children at risk for NDD without a later formal diagnosis.

Information Sources

The article search was performed systematically in the Cumulative Index to Nursing and Allied Health Literature, Embase, Medline, PsycINFO, and Scopus electronic databases. A combination of key terms, as well as free-text words, was included in the systematic search: "infant," "toddler," "intellectual developmental disorder," "developmental speech sound disorder," "autism spectrum disorder," "developmental learning disorder,"

"developmental coordination disorder," "attention deficit hyperactivity disorder," "stereotyped movement disorder," "fetal alcohol spectrum disorder," "sensory integration disorder," "motor impairment," and "motor delay." Search results were dated from the earliest record to the first week of June 2019. Reference lists from relevant articles were hand searched for eligible studies. The Medline search strategy is displayed in Supplemental Table 3.

Study Selection

One reviewer (Y.H.L.) screened all the search results, and 3 independent reviewers (M.L., A.F.-J., and J.D.) each screened one-third of the search results by applying the eligibility criteria on the title and abstract of identified articles and then conducting a full-text screening. Disagreements were resolved through discussion to achieve a final consensus on included articles.

Data Extraction and Quality Assessment

Four reviewers (Y.H.L., M.L., J.D., and A.F.-J.) independently extracted data from the eligible studies using standardized forms. Data included country of study, study design, participant characteristics, motor function assessment tool, outcome measure, results, and quality appraisal of the study. The methodologic quality of the studies was assessed by using the Standard Quality Assessment Criteria for Evaluating Primary Research Papers from a Variety of Fields checklist[25] (Supplemental Table 4). Study quality was classified on the basis of the calculated score percentages[26]: strong (>80%), good (70%–80%), adequate (50%–69%), or limited (<50%). Studies rated as limited quality were excluded from analysis.

Data Synthesis and Analysis

Narrative synthesis was used to synthesize data across all studies. Motor functions were categorized on the basis of the domains of the outcome measures: fine motor, gross motor, generalized motor, and general movement functions. Generalized motor function was derived from outcome measures that provided composite scores for fine and gross motor functions. In addition, a meta-analysis was used to synthesize data from studies involving children with later ASD because both mean and SD values of motor function outcomes were reported in most of those studies, whereas they were not reported in studies involving other children with later NDD. Data used in the meta-analysis were analyzed by age group (0–6, 7–12, 13–18, and 19–24 months). When SD values were not available, they were estimated from available confidence interval (CI) data, SEs, or other methods recommended by the Cochrane Collaboration.[27] Data represented in figures and graphical representations were extracted by using the WebPlotDigitizer software.[23] Standardized mean difference and 95% CI values for each motor outcome were calculated and presented in forest plots by using the Review Manager software version 5.3.[28] Random-effects models were used to calculate the pooled estimates and their CI. Statistical significance was assumed when the P value was <.05. The I^2 value was used to interpret the degree of heterogeneity.[27] The magnitude of the effect size, the standardized mean difference, was interpreted as follows: small, 0.20 to <0.50; medium, 0.50 to <0.80; and large, ≥0.80.[29]

RESULTS

Study Selection

In the search, we identified 7689 studies from across 5 databases. After eligibility screening, 25 studies were included in the systematic review, and 13 of these were included in the meta-analysis (Fig 1). In total, 1028 children had later NDD, and 74 861 were TD children. In 2 of the included studies, normative data were used as a comparator.

Study Characteristics

The main characteristics of the included studies are summarized in Table 1. Participants ranged between 0 and 24 months old at the time of motor function assessment. Later diagnoses of NDD included ADHD (2 studies), ASD (21 studies), DCD (1 study), FASD (2 studies), and pervasive developmental disorder not otherwise specified (PDD-NOS) (1 study). The motor function assessment tools used included the Ages and Stages Questionnaire, Second Edition[30] (ASQ-2), Bayley Scales of Infant Development, Second Edition[31] (BSID-II), Bayley Short Form Research Edition[32] (BSFR), Denver Developmental Screening Test[33] (DDST), General Movements Assessment[34] (GMA), Griffiths Mental Developmental Scales–Extended Revised[35] (GMDS-ER), Kyoto Scale of Psychological Development[36] (KSPD), Mullen Scales of Early Learning[37] (MSEL), Peabody Developmental Motor Scales, Second Edition[38] (PDMS-2), and Vineland Adaptive Behavior Scales, Second Edition[39] (VABS-II). Of these, the MSEL was the most frequently used motor function assessment tool.

In Table 2, we describe the motor outcomes reported in each study across the 4 age ranges. In one study,[40] both the MSEL and VABS-II were used to assess fine and gross motor functions; data from both motor assessment tools were displayed in forest plots, but only data from the MSEL were used in the calculation of the effect size.

Methodologic Quality of Included Studies

Classification of the quality of the included studies revealed that 12 studies were of strong quality, 4 were

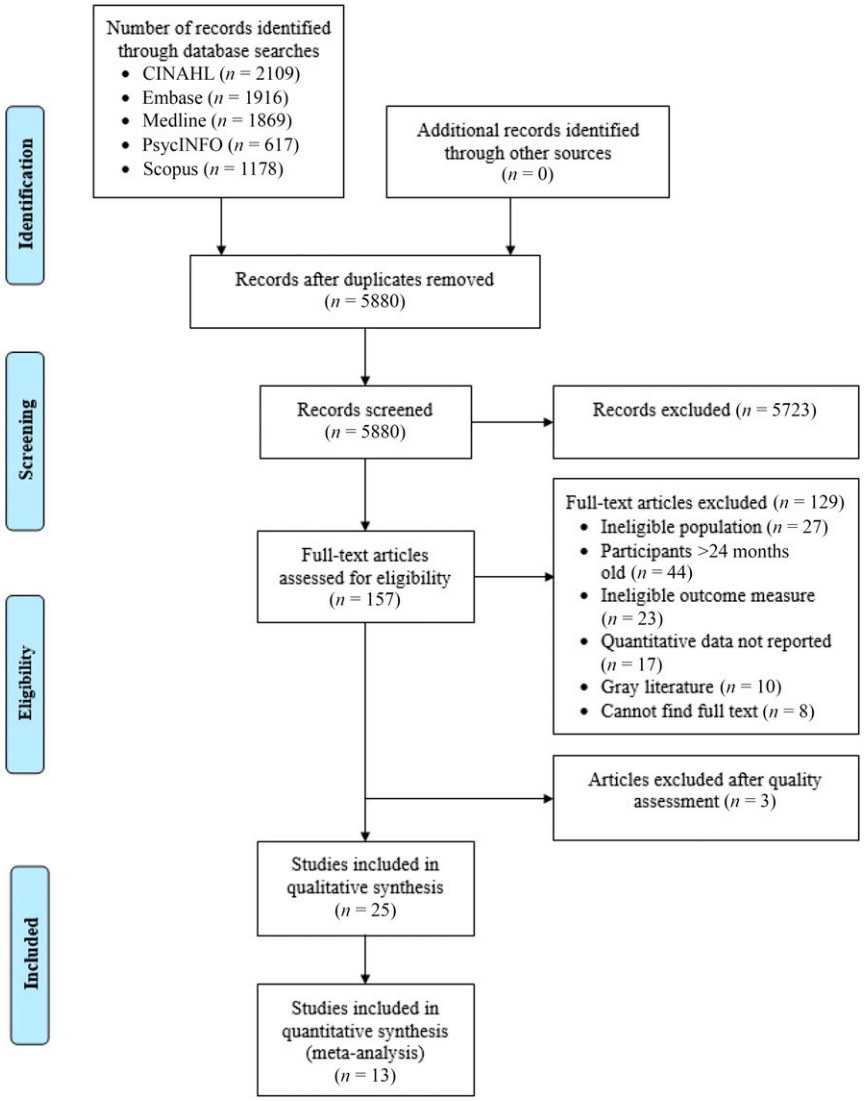

FIGURE 1
Preferred Reporting Items for Systematic Reviews and Meta-Analyses flow diagram of the included studies. CINAHL, Cumulative Index to Nursing and Allied Health Literature.

of good quality, and 9 were of adequate quality (Supplemental Table 5). Three studies identified as being of limited quality were excluded from analysis.

Early Motor Function at 0 to 6 Months

Fine Motor

Fine motor function of children with later ASD was examined in 8 studies by using the DDST, MSEL, and PDMS-2. In 5 studies,[41–45] the authors reported no difference in fine motor function between the later ASD and TD groups (mean age: 6 months). In contrast, the authors of 3 studies[44,46,47] found that children with later ASD (mean age: 6 months) demonstrated poorer fine motor function in relation to TD children.

A meta-analysis of 6 studies involving children with later ASD and TD children revealed an overall small effect size of 0.40 (95% CI −0.57 to −0.23; $P < .001$) (Fig 2A), indicating poorer fine motor function in the later ASD group. There was evidence of insignificant heterogeneity of the effect size (I^2 = 0%).

Gross Motor

Gross motor function of children with later ADHD and ASD was examined in 7 studies by using the DDST, KSPD, MSEL, and PDMS-2. In 4 studies,[43,44,46,47] the authors reported no difference in gross motor function between the later ASD and TD groups (mean age: 6 months). In contrast, the authors of 3 studies[42,48,49] reported that children with later ADHD and ASD (ADHD, 1 study; ASD, 2 studies; age range: 3–6 months) showed poorer gross motor function compared with TD children.

A meta-analysis of 5 studies involving children with later ASD and TD children revealed an overall small effect size of 0.24 (95% CI −0.46 to −0.03; P = .03) (Fig 2B), indicating poorer gross motor function in the later ASD group. There was evidence of insignificant heterogeneity of the effect size (I^2 = 20%).

Generalized Motor Function

Generalized motor function of children with later ASD and FASD was examined in 2 studies by using the BSID-II and VABS-II. In both studies,[42,50] the authors reported that children with later ASD and FASD (ASD, 1 study; FASD, 1 study; mean age: 6 months) showed poorer generalized motor function when compared with TD group. A meta-analysis was not performed because of the availability of only one study in which generalized motor function in children with later ASD was reported.

General Movements

General movements of children with later ADHD, ASD, DCD, and PDD-NOS was examined in 3 studies by using the GMA. In one prospective study,[51] the authors assessed GMA in 5 children with 3 different NDD (ADHD, n = 1; DCD, n = 3; PDD-NOS, n = 1) and 23 TD children (age range: 3–5

TABLE 1 Study Characteristics

Study	Design	Participants (Sample Size, Age, Location, Age at Diagnosis)	Assessment Tools and Outcomes	Major Findings	Quality Appraisal
Choi et al[41]	Prospective cohort	Children with ASD (n = 30; 27 boys), high-risk children without ASD diagnosis (n = 71; 33 boys), and TD children (n = 69; 38 boys); age range: 6–24 mo; United States; ASD diagnosed at 18–36 mo	MSEL; fine motor subscale	Fine motor, 6 mo: no group difference between ASD, high-risk without ASD diagnosis, and TD groups (P = .20); fine motor, 12 mo: ASD group (mean = 16.5, SD = 2.08) showed poorer motor function compared with high-risk without ASD diagnosis group (mean = 17.27, SD = 1.80) (P = .015); fine motor, 18 mo: ASD group (mean = 20.36, SD = 1.66) showed poorer motor function compared with TD group (mean = 20.96, SD = 1.54) (P = .02), no group difference between ASD and high-risk without ASD diagnosis groups; fine motor, 24 mo: ASD group (mean = 24.12, SD = 2.42) showed poorer motor function compared with high-risk without ASD diagnosis (mean = 25.13, SD = 2.12) and TD groups (mean = 25.56, SD = 2.59) (P = .04)	Strong: 19 of 22 (86%)
Davies et al[57]	Prospective cohort	Children with FASD (n = 29; 11 boys) and TD children (n = 35; 13 boys); age range: 7–12 mo; South Africa; FASD diagnosed at 5 y	GMDS-ER; eye-hand coordination and locomotion subscales	Eye-hand coordination, 7–12 mo: no group difference between FASD and TD groups (P = .13); locomotion, 7–12 mo: FASD group showed poorer motor function (mean = 88.9) compared with TD group (mean = 97.3) (P = .034)	Strong: 18 of 22 (82%)
Emerson et al[64]	Prospective cohort	Children with ASD (n = 11; 11 boys) and high-risk children without ASD diagnosis (n = 48; 30 boys); mean age: 24 mo; United States; ASD diagnosed at 24 mo	MSEL; fine and gross motor subscales	Fine motor, 24 mo: group difference was not reported (ASD: mean = 24.08, SD = 1.0; high-risk without ASD diagnosis: mean = 23.84, SD = 0.3); gross motor, 24 mo: group difference was not reported (ASD: mean = 24.64, SD = 0.5; high-risk without ASD diagnosis: mean = 25.79, SD = 0.4)	Adequate: 11 of 22 (50%)
Estes et al[42]	Prospective cohort	High-risk children with ASD (n = 31; 26 boys), moderate-risk children with ASD (n = 18; 15 boys), high-risk children without ASD diagnosis (n = 161; 88 boys), and TD children (n = 98; 55 boys); age range: 6–24 mo; United States; ASD diagnosed at 24 mo	MSEL; fine and gross motor subscales	Fine motor, 6 mo: no group difference between high-risk ASD, moderate-risk ASD, high-risk without ASD diagnosis, and TD groups (P = .54); gross motor, 6 mo: high-risk ASD group (LSM = 43.7, SE = 1.5) showed poorer motor function compared with TD group (LSM = 50.8, SE = 0.9) (P = .014); fine motor, 12 mo: high-risk ASD group (LSM = 53.9, SE = 1.7) showed poorer motor function compared with TD group (LSM = 59.6, SE = 0.7) ($P <$ .001); gross motor, 12 mo: high-risk ASD group (LSM = 42.7, SE = 2.2) showed poorer motor function compared with TD group (LSM = 50.4, SE = 1.2) ($P <$ .001); fine motor, 24 mo: high-risk ASD group (LSM = 39.9, SE =	Strong: 22 of 22 (100%)

TABLE 1 Continued

Study	Design	Participants (Sample Size, Age, Location, Age at Diagnosis)	Assessment Tools and Outcomes	Major Findings	Quality Appraisal
				1.7) showed poorer motor function compared with moderate-risk ASD (LSM = 42.9, SE = 2.3) and TD groups (LSM = 54.6, SE = 1.0) ($P < .001$); gross motor, 24 mo: high-risk ASD group (LSM = 38.4, SE = 1.6) showed poorer motor function compared with moderate-risk ASD (LSM = 43.9, SE = 2.1) and TD groups (LSM = 52.0, SE = 0.9) ($P < .001$)	
Estes et al[42]	Prospective cohort	High-risk children with ASD (n = 31; 26 boys), moderate-risk children with ASD (n = 18; 15 boys), high-risk children without ASD diagnosis (n = 161; 88 boys), and TD children (n = 98; 55 boys); age range: 6–24 mo; United States; ASD diagnosed at 24 mo	VABS-II; motor subscale	Generalized motor, 6 mo: high-risk ASD group (LSM = 84.3, SE = 2.3) showed poorer motor function compared with TD group (LSM = 95.5, SE = 1.3) ($P < .005$); generalized motor, 12 mo: high-risk ASD group (LSM = 94.1, SE = 1.9) showed poorer motor function compared with TD group (LSM = 103.3, SE = 1.0) ($P < .01$); generalized motor, 24 mo: high-risk ASD group (LSM = 92.9, SE = 1.7) showed poorer motor function compared with TD group (LSM = 102.8, SE = 0.9) ($P < .001$)	Strong: 22 of 22 (100%)
Gurevitz et al[48]	Prospective cohort	Children with ADHD (n = 58; 40 boys) and TD children (n = 58; 38 boys); ages: 3, 9, and 18 mo; Israel; ADHD diagnosed at 8 y	DDST; fine and gross motor subscales	Gross motor, 3 mo: 44.8% of ADHD group showed poorer motor function compared with 19% of TD group (P = .002); fine motor, 9 mo: no group difference between ADHD and TD groups (P = .122); gross motor, 9 mo: 34.5% of ADHD group showed poorer motor function compared with 13.8% of TD group (P = .008); fine motor, 18 mo: no group difference between ADHD and TD groups (P = .219); gross motor, 18 mo: 12.1% of ADHD group showed poorer motor function compared with 1.7% of TD group (P = .03)	Strong: 19 of 22 (86%)
Heathcock et al[76]	Case-control	Children with ASD (n = 5), high-risk children without ASD diagnosis (n = 18), and TD children (n = 14); mean age: 6 mo; United States; ASD diagnosed at 24–48 mo	AIMS	Motor scores of children with ASD were not reported.	Limited: 10 of 22 (46%)
Iverson et al[46]	Prospective cohort	Children with ASD (n = 69; 49 boys) and TD children (n = 188; 107 boys); mean age: 6 mo; United States; ASD diagnosed at 3 y	MSEL; fine and gross motor subscales	Fine motor, 6 mo: ASD group showed poorer motor function (mean = 45.9, SD = 9.1) compared with TD group (mean = 50.1, SD = 7.9) (P = .004); gross motor, 6 mo: no group difference between ASD and TD groups	Strong: 18 of 22 (82%)
Jeans et al[58]	Prospective cohort	Children with ASD (n = 100; 70 boys) and TD children (n = 7700; 3773 boys); age range: 9–24 mo; United States; ASD diagnosed at 4 y	BSFR; motor index	Generalized motor, 9 mo: no group difference between ASD and TD groups (P = .982); generalized motor, 24 mo: ASD group (mean	Strong: 21 of 22 (96%)

TABLE 1 Continued

Study	Design	Participants (Sample Size, Age, Location, Age at Diagnosis)	Assessment Tools and Outcomes	Major Findings	Quality Appraisal
				= 74.69, SD = 5.78) showed poorer motor function compared with TD group (mean = 81.74, SD = 4.78) ($P < .001$)	
Kihara and Nakamura[49]	Prospective cohort	Children with ASD (n = 35; 22 boys) and TD children (n = 169; 63 boys); age range: 6–18 mo; Japan; ASD diagnosed at 3–6 y	KSPD; postural motor	Gross motor, postural motor, 6 mo: ASD group (mean = 84) showed poorer motor function compared with TD group (mean = 93) ($P <$ .01); gross motor, postural motor, 18 mo: ASD group (mean = 90) showed poorer motor function compared with TD group (mean = 98) ($P < .05$)	Good: 16 of 22 (73%)
Landa and Garrett-Mayer[43]	Prospective cohort	Children with ASD (n = 24) and TD children (n = 52); ages: 6, 14, and 24 mo; United States; ASD diagnosed at 2 y	MSEL; fine and gross motor subscales	Fine motor, 6 mo: no group difference between ASD and TD groups; gross motor, 6 mo: no group difference between ASD and TD groups; fine motor, 14 mo: ASD group showed poorer motor function (mean = 50.42, SD = 10.21) compared with TD group (mean = 57.38, SD = 7.35) ($P = .01$); gross motor, 14 mo: children with ASD showed poorer motor function (mean = 47.46, SD = 12.36) compared with TD children (mean = 58.00, SD = 10.48) ($P < .001$); fine motor, 24 mo: ASD group showed poorer motor function (mean = 36.71, SD = 14.23) compared with TD group (mean = 52.58, SD = 11.07) ($P < .001$); gross motor, 24 mo: ASD group showed poorer motor function (mean = 36.21, SD = 9.31) compared with TD group (mean = 51.94, SD = 11.02) ($P < .001$)	Good: 16 of 22 (73%)
Landa et al[77]	Prospective cohort	Children with ASD (n = 52; 43 boys) and TD children (n = 121; 53 boys); age range: 14–24 mo; United States; ASD diagnosed at 30–36 mo	MSEL; fine and gross motor subscales	Motor scores of children with ASD cannot be identified.	Limited: 11 of 22 (46%)
Landa et al[59]	Prospective cohort	Children with early ASD (n = 28; 22 boys), children with later ASD (n = 26; 22 boys), and TD children (n = 181; 84 boys); age range: 14 and 24 mo; United States; ASD diagnosed at 30–36 mo	MSEL; fine motor subscale	Fine motor, 14 mo: no group difference between early ASD and TD groups, later ASD group (mean = 16.9) showed poorer motor function compared with TD children (mean = 18.1) ($P = .008$); fine motor, 24 mo: no group difference between early ASD, later ASD, and TD groups	Adequate: 13 of 22 (59%)
LeBarton and Iverson[62]	Prospective cohort	Children with ASD (n = 7; 4 boys), high-risk children without ASD diagnosis (n = 27; 13 boys), and TD children (n = 25; 10 boys); mean age: 24 mo; United States; ASD diagnosed at 3 y	MSEL; fine motor subscale	Fine motor, 24 mo: ASD group (mean = 18.29, SD = 3.15) showed poorer motor function compared with high-risk without ASD diagnosis group (mean = 24, SD = 1.89) ($P <$ .01); fine motor data for TD group was not reported	Adequate: 15 of 22 (68%)

TABLE 1 Continued

Study	Design	Participants (Sample Size, Age, Location, Age at Diagnosis)	Assessment Tools and Outcomes	Major Findings	Quality Appraisal
LeBarton and Landa[44]	Prospective cohort	Children with ASD (n = 20; 12 boys), high-risk children without ASD diagnosis (n = 69; 40 boys), and TD children (n = 51; 27 boys); mean age: 6 mo; United States; ASD diagnosed at 24–36 mo	PDMS-2; grasping, visual-motor integration, and stationary subscales	Fine motor, grasping, 6 mo: no group difference between ASD, high-risk without ASD diagnosis, and TD groups; fine motor, visual-motor integration, 6 mo: ASD group (mean = 31.05, SE = 1.59) showed poorer motor function compared with TD group (mean = 33.24, SE = 0.83) (P = .032), no group difference between ASD and high-risk without ASD diagnosis groups (P = .171); gross motor, stationary, 6 mo: no group difference between ASD, high-risk without ASD diagnosis, and TD groups (P = .069)	Strong: 19 of 22 (86%)
Leonard et al[40]	Prospective cohort	Children with ASD (n = 17; 11 boys), high-risk children without ASD diagnosis (n = 24; 7 boys), and TD children (n = 50; 21 boys); ages: 7, 14, and 24 mo; United Kingdom; ASD diagnosed at 36 mo	MSEL; fine and gross motor subscales	Fine motor, 7 mo: ASD (mean = 49.81, SD = 11.08) and high-risk without ASD diagnosis groups (mean = 53.54, SD = 11.11) showed poorer motor function compared with TD group (mean = 57.79, SD = 9.49) (P = .01); gross motor, 7 mo: ASD (mean = 46.06, SD = 12.58) and high-risk without ASD diagnosis groups (mean = 45.17, SD = 8.39) showed poorer motor function compared with TD group (mean = 50.17, SD = 8.98) (P = .01); fine motor, 14 mo: ASD (mean = 51.18, SD = 12.91) and high-risk without ASD diagnosis groups (mean = 56.74, SD = 12.45) showed poorer motor function compared with TD group (mean = 61.28, SD = 9.23) (P = .01); gross motor, 14 mo: no group difference between ASD, high-risk without ASD diagnosis, and TD groups; fine motor, 24 mo: no group difference between ASD, high-risk without ASD diagnosis, and TD groups; gross motor, 24 mo: ASD (mean = 44.00, SD = 13.21) and high-risk without ASD diagnosis groups (mean = 44.59, SD = 11.35) showed poorer motor function compared with TD group (mean = 59.89, SD = 8.08) ($P < .001$)	Adequate: 14 of 22 (64%)
Leonard et al[40]	Prospective cohort	Children with ASD (n = 17; 11 boys), high-risk children without ASD diagnosis (n = 24; 7 boys), and TD children (n = 50; 21 boys); ages: 7, 14, and 24 mo; United Kingdom; ASD diagnosed at 36 mo	VABS-II; fine and gross motor subscales	Fine motor, 7 mo: ASD (mean = 13.53, SD = 2.13) and high-risk without ASD diagnosis groups (mean = 14.26, SD = 3.36) showed poorer motor function compared with TD group (mean = 15.53, SD = 2.56) (P = .001); gross motor, 7 mo: ASD (mean = 12.82, SD = 3.47) and high-risk without ASD diagnosis groups (mean = 13.04, SD = 3.31) showed poorer	Adequate: 14 of 22 (64%)

TABLE 1 Continued

Study	Design	Participants (Sample Size, Age, Location, Age at Diagnosis)	Assessment Tools and Outcomes	Major Findings	Quality Appraisal
				motor function compared with TD group (mean = 14.60, SD = 2.62) (P = .001); fine motor, 14 mo: ASD (mean = 15.71, SD = 3.06) and high-risk without ASD diagnosis groups (mean = 15.24, SD = 2.10) showed poorer motor function compared with TD group (mean = 17.27 = 2.18) (P = .001); gross motor, 14 mo: no group difference between ASD, high-risk without ASD diagnosis, and TD groups; fine motor, 24 mo: no group difference between ASD, high-risk without ASD diagnosis, and TD groups; gross motor, 24 mo: no group difference between ASD, high-risk without ASD diagnosis, and TD groups (P = .05)	
Leonard et al[56]	Prospective cohort	Children with ASD (n = 17; 11 boys), high-risk children without ASD diagnosis (n = 36; 10 boys), and TD children (n = 48; 17 boys); mean age: 7 mo; United Kingdom; ASD diagnosed at 36 mo	MSEL; fine and gross motor subscales	Fine motor, 7 mo: group difference was not reported (ASD: mean = 49.81, SD = 11.08; high-risk without ASD diagnosis: mean = 53.67, SD = 10.26; TD: mean = 57.79, SD = 9.49); gross motor, 7 mo: group difference was not reported (ASD: mean = 46.06, SD = 12.58; high-risk without ASD diagnosis: mean = 45.33, SD = 8.84; TD: mean = 50.17, SD = 8.98)	Adequate: 14 of 22 (64%)
Libertus et al[47]	Prospective cohort study	Children with ASD (n = 22; 9 boys), high-risk children without ASD diagnosis (n = 57; 24 boys), and TD children (n = 22; 17 boys); mean age: 6 mo; United States; ASD diagnosed at 36 mo	MSEL; fine and gross motor subscales	Fine motor, 6 mo: ASD (mean = 44.18, SD = 9.90) and high-risk without ASD diagnosis groups (mean = 45.53, SD = 10.02) showed poorer motor function compared with TD group (mean = 51.23, SD = 8.11) ($P < .05$); gross motor, 6 mo: no group difference between ASD, high-risk without ASD diagnosis, and TD groups	Strong: 19 of 22 (86%)
Lloyd et al[63]	Retrospective cohort	Children with ASD (n = 34; 28 boys); mean age: 20 mo old; United States	VABS-II; fine and gross motor subscales	Fine motor, 14–24 mo: motor function of ASD group (mean age equivalent = 16.88 mo, SD = 5.06) was shown to be 3.9 mo behind normative data (mean age equivalent = 16.50 mo, SD = 2.86); gross motor, 14–24 mo: motor function of ASD group (mean age equivalent = 18.45 mo, SD = 3.43) was shown to be 3.5 mo behind normative data (mean age equivalent = 17.47 mo, SD = 3.18)	Strong 18 of 20 (90%)
Øien et al[60]	Prospective cohort	Children with ASD (false-negative) (n = 216; 183 boys) and TD children (true-negative) (n = 65 394; 33 163 boys); mean age: 18 mo; Norway; ASD diagnosed at ≥40 mo	ASQ-2; fine and gross motor subscales	Fine motor, 18 mo: boys with ASD showed poorer motor function (mean = 8.76, SD = 1.78) compared with TD boys (mean = 9.39, SD = 1.27) ($P < .001$), girls with ASD showed	Strong: 18 of 22 (82%)

TABLE 1 Continued

Study	Design	Participants (Sample Size, Age, Location, Age at Diagnosis)	Assessment Tools and Outcomes	Major Findings	Quality Appraisal
				poorer motor function (mean = 8.28, SD = 2.34) compared with TD girls (mean = 9.28, SD = 1.37) ($P < .001$); gross motor, 18 mo: boys with ASD showed poorer motor function (mean = 8.83, SD = 2.29) compared with TD boys (mean = 9.49, SD = 1.49) ($P < .001$), girls with ASD showed poorer motor function (mean = 6.36, SD = 3.85) compared with TD girls (mean = 9.46, SD = 1.49) ($P < .001$)	
Ozonoff et al[45]	Prospective cohort	Children with ASD (n = 51; 43 boys), high-risk children without ASD diagnosis (n = 160; 70 boys), and TD children (n = 116; 63 boys); ages: 6, 12, and 24 mo; United States; ASD diagnosed at 36 mo	MSEL; fine motor subscale	Fine motor, 6 mo: no group difference between ASD, high-risk without ASD diagnosis, and TD groups; fine motor, 12 mo: ASD group (mean = 13.9) showed poorer motor function compared with TD group (mean = 14.6) ($P < .05$); fine motor, 24 mo: group difference was not reported (ASD: mean = 23; high-risk without ASD diagnosis: mean = 25.3; TD: mean = 25.8)	Good: 16 of 22 (73%)
Ozonoff et al[61]	Prospective cohort	Children with ASD (true-positives) (n = 38) and TD children (true-negatives) (n = 293); age range: 18–24 mo; United States; ASD diagnosed at 36 mo	MSEL; fine motor subscale	Fine motor, 18 mo: group difference was not reported (ASD: mean = 44.3 [95% CI 41.6 to 47.1]; TD: mean = 52.8 [95% CI 51.3 to 54.4]); fine motor, 24 mo: group difference was not reported (ASD: mean = 39.4 [95% CI 36.8 to 42.0]; TD: mean = 51.0 [95% CI 49.6 to 52.4])	Strong: 20 of 22 (91%)
Phagava et al[52]	Case-control	Children with ASD (n = 20; 17 boys) and TD children (n = 20; 10 boys); age range: 6–21 wk; Georgia	GMA; general movements optimality score	General movements, 1–3 mo: ASD group (mean = 16.9) showed poorer motor function compared with TD group (mean = 23.9) ($P < .001$)	Adequate: 11 of 22 (50%)
Serdarevic et al[78]	Prospective cohort	Children with ASD (n = 30); age range: 2–5 mo; Netherlands; ASD diagnosed at 6 y	Touwen's Neurodevelopmental Examination; muscle tone	Motor scores of children with ASD cannot be identified.	Limited; 9 of 20 (45%)
Sowell et al[50]	Case-control	Children with FASD (n = 90; 47 boys) and TD children (n = 47; 25 boys); age range: 6–12 mo; Ukraine	BSID-II; psychomotor development index	Generalized motor, 6 mo: FASD group (mean = 79.79, SE = 1.32) showed poorer motor function compared with TD group (mean = 96.07, SE = 1.06) ($P < .05$); generalized motor, 12 mo: FASD group (mean = 87.05, SE = 1.72) showed poorer motor function compared with TD group (mean = 101.94, SE = 1.32) ($P < .05$)	Good: 16 of 22 (73%)
St John et al[55]	Prospective cohort	Children with ASD (n = 23; 17 boys), high-risk children without ASD diagnosis (n = 101; 57 boys), and TD children (n = 50; 29 boys); mean age: 12 mo; United States; ASD	MSEL; fine and gross motor subscales	Fine motor, 12 mo: ASD group (mean = 54.35, SD = 9.00) showed poorer motor function compared with high-risk without ASD diagnosis (mean = 58.18, SD = 8.58) and TD	Strong: 20 of 22 (91%)

TABLE 1 Continued

Study	Design	Participants (Sample Size, Age, Location, Age at Diagnosis)	Assessment Tools and Outcomes	Major Findings	Quality Appraisal
		diagnosed at 24 mo; children with ASD (n = 19; 14 boys), high-risk children with ASD diagnosis (n = 106; 63 boys), and TD children (n = 49; 24 boys); mean age: 24 mo; United States; ASD diagnosed at 24 mo		groups (mean = 60.02, SD = 8.23) (P = .033); gross motor, 12 mo: ASD group (mean = 44.78, SD = 13.18) showed poorer motor function compared with high-risk without ASD diagnosis (mean = 47.77, SD = 11.87) and TD groups (mean = 52.02, SD = 12.19) (P = .037); fine motor, 24 mo: ASD group (mean = 45.89, SD = 9.47) showed poorer motor function compared with high-risk without ASD diagnosis (mean = 49.75, SD = 8.77) and TD groups (mean = 55.14, SD = 8.79) ($P <$ .001); gross motor, 24 mo: ASD group (mean = 42.26, SD = 8.63) showed poorer motor function compared with high-risk without ASD diagnosis (mean = 49.82, SD = 9.15) and TD groups (mean = 52.04, SD = 7.29) ($P <$ .001)	
Young et al[54]	Prospective cohort	Children with ASD (n = 24; 21 boys) and TD children (n = 75; 42 boys); age range: 12–24 mo; United States; ASD diagnosed at 3 y	MSEL; fine motor subscale	Fine motor, 12 mo: no group difference between ASD and TD groups; fine motor, 18 mo: no group difference between ASD and TD groups; fine motor, 24 mo: no group difference between ASD and TD groups	Adequate: 15 of 22 (68%)
Yuge et al[51]	Prospective cohort	Children with DCD (n = 3; 1 boy), children with PDD-NOS (n = 1; 0 boys), children with ADHD (n = 1; 1 boy), and TD children (n = 23; 12 boys); age range: 3–5 mo; Japan; NDD diagnosed at 5 y	GMA; general movements optimality score	General movements, 3–5 mo: group difference was not reported (ADHD: mean = 26; DCD: mean = 22; PDD-NOS: mean = 26; TD: median = 24 [IQR 22–26])	Adequate: 12 of 22 (55%)
Zappella et al[53]	Retrospective cohort	Children with ASD (n = 10; 10 boys) and without ASD (n = 8; 8 boys); age range: 1–6 mo; Italy; ASD diagnosed at 3–7 y	GMA; general movements	General movements, 1–6 mo: 87.5% (7 of 8) of ASD group showed abnormal general movements; inadequate information on 2 infants with later ASD	Adequate: 14 of 22 (64%)

AIMS, Alberta Infant Motor Scale; IQR, interquartile range; LSM, least square mean.

TABLE 2 Summary of the Domains of Motor Function Examined in the Included Studies

Study	Fine Motor	Gross Motor	Generalized Motor Function	General Movements
0–6 mo				
Choi et al[41]	X	—	—	—
Estes et al[42]	X	X	X	—
Gurevitz et al[48]	—	X	—	—
Iverson et al[46]	X	X	—	—
Kihara and Nakamura[49]	—	X	—	—
Landa and Garrett-Mayer[43]	X	X	—	—
LeBarton and Landa[44]	X	X	—	—
Libertus et al[47]	X	X	—	—
Ozonoff et al[45]	X	—	—	—
Phagava et al[52]	—	—	—	X
Sowell et al[50]	—	—	X	—
Yuge et al[51]	—	—	—	X
Zappella et al[53]	—	—	—	X
13–18 mo				
Choi et al[41]	X	—	—	—
Gurevitz et al[48]	X	X	—	—
Kihara and Nakamura[49]	—	X	—	—
Landa and Garrett-Mayer[43]	X	X	—	—
Landa et al[59]	X	—	—	—
Leonard et al[40]	X	X	—	—
Øien et al[60]	X	X	—	—
Ozonoff et al[61]	X	—	—	—
Young et al[54]	X	—	—	—
7–12 mo				
Choi et al[41]	X	—	—	—
Davies et al[57]	X	X	—	—
Estes et al[42]	X	X	X	—
Gurevitz et al[48]	X	X	—	—
Jeans et al[58]	—	—	X	—
Leonard et al[40]	X	X	—	—
Leonard et al[56]	X	X	—	—
Ozonoff et al[45]	X	—	—	—
Sowell et al[50]	—	—	X	—
St John et al[55]	X	X	—	—
Young et al[54]	X	—	—	—
19–24 mo				
Choi et al[41]	X	—	—	—
Emerson et al[64]	X	X	—	—
Estes et al[42]	X	X	X	—
Jeans et al[58]	—	—	X	—
Landa and Garrett-Mayer[43]	X	X	—	—
Landa et al[59]	X	—	—	—
LeBarton and Iverson[62]	X	—	—	—
Leonard et al[40]	X	X	—	—
Lloyd et al[63]	X	X	—	—
Ozonoff et al[45]	X	—	—	—
Ozonoff et al[61]	X	—	—	—
St John et al[55]	X	X	—	—
Young et al[54]	X	—	—	—

Total number of outcomes assessed: fine motor = 37; gross motor = 24; generalized motor function = 7; general movements = 3. X, specified domain of motor function examined in the study; —, not applicable.

months) and found that the general movement optimality scores of children with later-diagnosed ADHD, DCD, and PDD-NOS were in the normal range of those of TD children. It is important to note that the findings by Yuge et al[51] are limited by a small sample size and included insufficient quantitative data to compare general movement function between different groups with later-diagnosed NDD and the TD group. In contrast, the authors of one retrospective study[52] compared the general movement optimality scores between 20 children with later ASD (age range: 1–3 months) and 20 TD children and found that those with

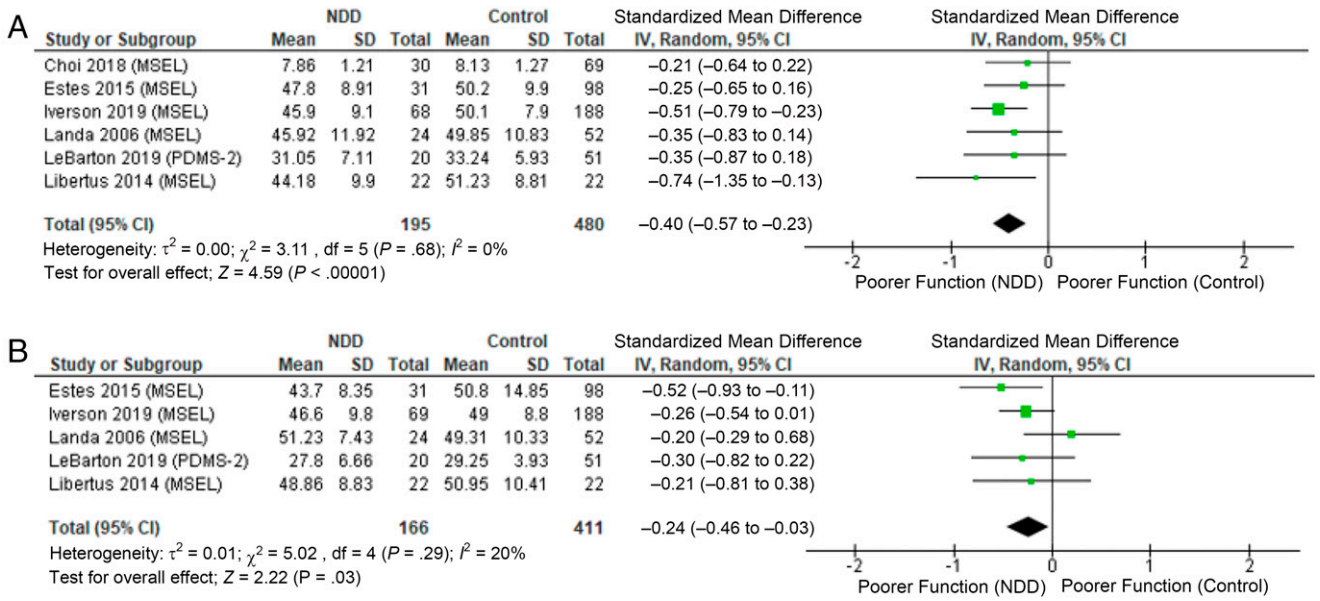

FIGURE 2

A and B, Forest plots of the comparison of fine motor function (A) and gross motor function (B) in children (0–6 months) with later diagnoses of ASD versus controls. The motor function assessment used is indicated next to each study. df, degree of freedom; IV, inverse variance.

later ASD demonstrated lower optimality scores, indicating poorer general movement function. The authors of another retrospective study[53] found that 87.5% (7 of 8) of children with later ASD showed abnormal general movements within the first 6 months of life. A meta-analysis of the studies involving children with later ASD was not possible because SDs could not be obtained.

Early Motor Function at 7 to 12 Months

Fine Motor

Fine motor function of children with later ADHD and ASD was examined in 8 studies by using the DDST, MSEL, and VABS-II. In 2 studies,[48,54] the authors reported no difference in fine motor function between the later ADHD and ASD groups (ADHD, 1 study; ASD, 1 study; age range: 9–12 months) and the TD group. In contrast, the authors of 5 studies[40–42,45,55] found that children with later ASD (age range: 7–12 months) demonstrated poorer fine motor function in relation to TD children. Statistical difference between the later ASD and TD groups was not reported in one study.[56]

A meta-analysis of 6 studies involving children with later ASD and TD children revealed an overall moderate effect size of 0.79 (95% CI −1.06 to −0.52; $P < .001$) (Fig 3A), indicating poorer fine motor function in the later ASD group. There was evidence of moderate heterogeneity of the effect size (I^2 = 44%).

Gross Motor

Gross motor function of children with later ADHD, ASD, and FASD was examined in 6 studies by using the DDST, GMDS-ER, MSEL, and VABS-II. In one study,[57] the authors reported no difference in gross motor function between the later FASD (age range: 7–12 months) and TD groups. In contrast, the authors of 5 studies[40,42,48,55,57] found that children with later ADHD, ASD, and FASD (ADHD, 1 study; ASD, 3 studies; FASD, 1 study; age range: 7–12 months) demonstrated poorer gross motor function in relation to TD children.

A meta-analysis of 3 studies involving children with later ASD and TD children revealed an overall moderate effect size of 0.56 (95% CI −0.84 to −0.29; $P < .001$) (Fig 3B), indicating poorer gross motor function in the later ASD group. There was evidence of insignificant heterogeneity of the effect size (I^2 = 0%).

Generalized Motor Function

Generalized motor function of children with later ASD and FASD was examined in 3 studies by using the BSID-II, BSFR, and VABS-II. In one study,[58] the authors reported no difference in generalized motor function between the later ASD (mean age: 9 months) and TD groups. In contrast, the authors of 2 studies[42,50] found that children with later ASD and FASD (ASD, 1 study; FASD, 1 study; mean age: 12 months) demonstrated poorer generalized motor function in relation to TD children.

A meta-analysis of 3 studies involving children with later ASD and TD children revealed an overall nonsignificant effect size of 0.50 (95% CI −1.25 to 0.24; P = .18) (Fig 3C), indicating comparable generalized motor function between

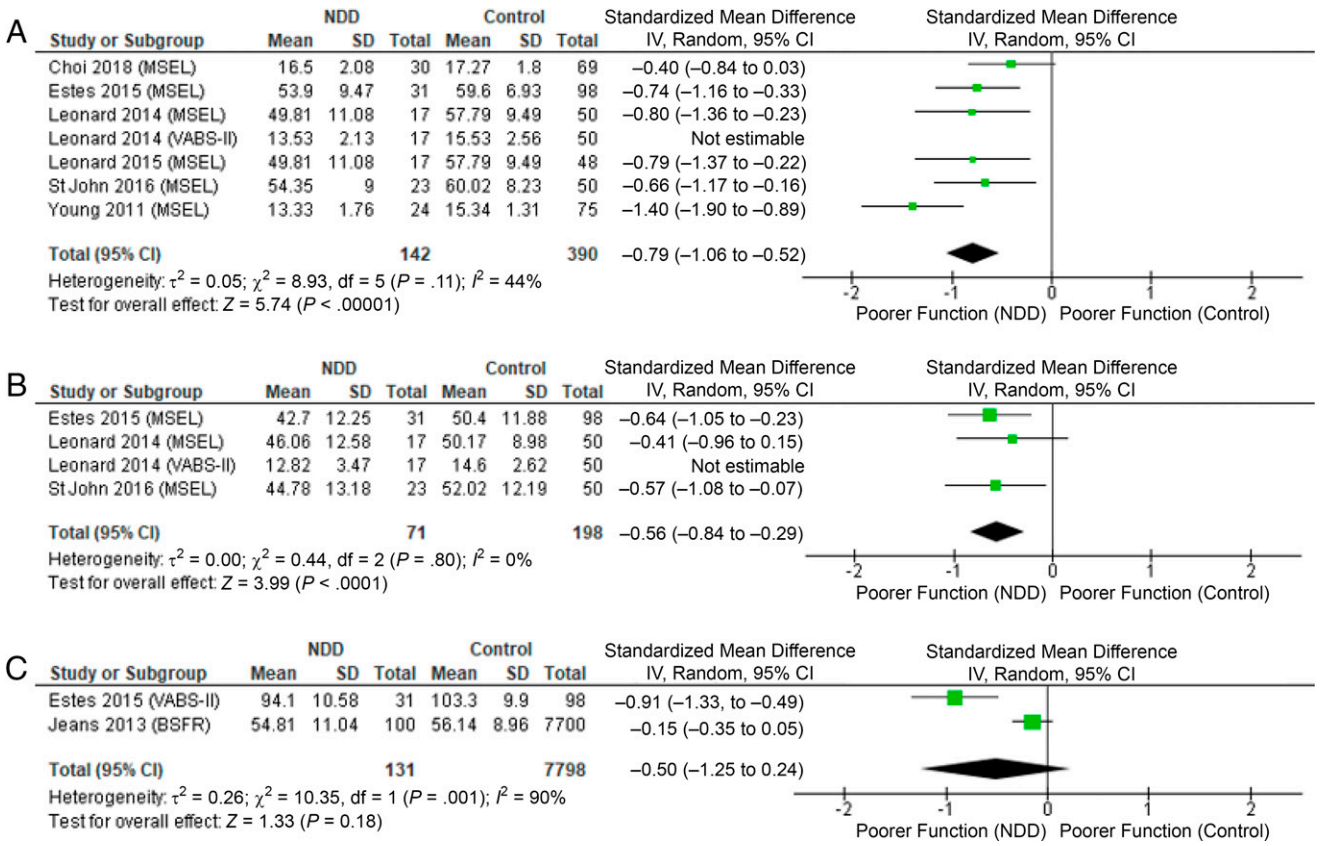

FIGURE 3

A–C, Forest plots of the comparison of fine motor function (A), gross motor function (B), and generalized motor function (C) in children (7–12 months) with later diagnoses of ASD versus controls. The motor function assessment used is indicated next to each study. df, degree of freedom; IV, inverse variance.

the later ASD and TD groups. There was evidence of considerable heterogeneity of the effect size (I^2 = 90%).

Early Motor Function at 13 to 18 Months

Fine Motor

Fine motor function of children with later ASD was examined in 8 studies by using the ASQ, DDST, MSEL, and VABS-II. In 2 studies,[48,54] the authors reported no difference in fine motor function between the later ASD and TD groups (mean age: 18 months). In contrast, the authors of 5 studies[40,41,43,59,60] found that children with later ASD (age range: 14–18 months) demonstrated poorer fine motor function in relation to TD children. Statistical difference between the later ASD and TD groups was not reported in one study.[61]

A meta-analysis of 6 studies involving children with later ASD and TD children revealed an overall moderate effect size of 0.72 (95% CI −0.95 to −0.50; $P < .001$) (Fig 4A), indicating poorer fine motor function in the later ASD group. There was evidence of substantial heterogeneity of the effect size (I^2 = 62%).

Gross Motor

Gross motor function of children with later ADHD and ASD was examined in 5 studies by using the ASQ, DDST, KSPD, MSEL, and VABS-II. In one study,[40] the authors reported no difference in gross motor function between the later ASD and TD groups (mean age: 14 months). In contrast, the authors of 4 studies[43,48,49,60] found that children with later ADHD and ASD (ADHD, 1 study; ASD, 3 studies; age range: 14–18 months) demonstrated poorer gross motor function in relation to TD children.

A meta-analysis of 3 studies involving children with later ASD and TD children revealed an overall large effect size of 1.11 (95% CI −1.98 to −0.24; $P = .01$) (Fig 4B), indicating poorer gross motor function in the later ASD group. There was evidence of considerable heterogeneity of the effect size (I^2 = 96%).

Early Motor Function at 19 to 24 Months

Fine Motor

Fine motor function of children with later ASD was examined in 12 studies by using the MSEL and VABS-II. In 3 studies,[40,54,59] the authors reported no difference in fine motor function between the later ASD and TD groups

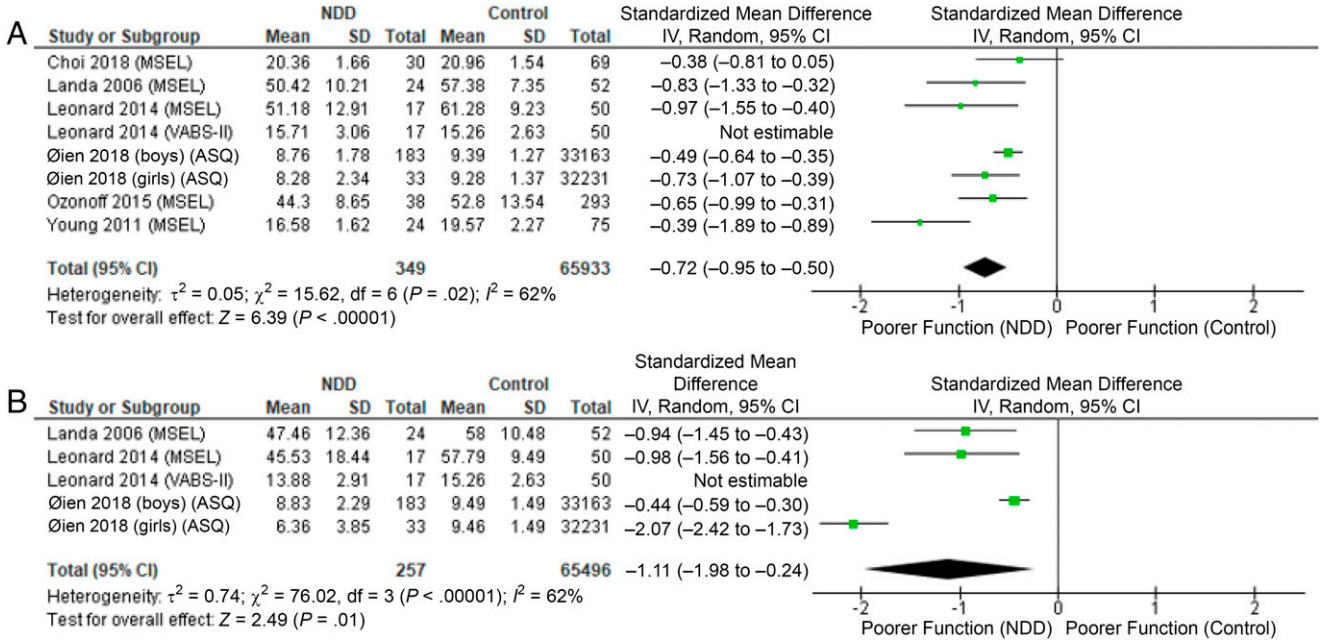

FIGURE 4

A and B, Forest plots of the comparison of fine motor function (A) and gross motor function (B) in children (13–18 months) with later diagnoses of ASD versus control. The motor function assessment used is indicated next to each study. df, degree of freedom; IV, inverse variance.

(mean age: 24 months). In contrast, the authors of 6 studies[41–43,55,62,63] found that children with later ASD (mean age: 24 months) demonstrated poorer fine motor function in relation to TD children or normative data. Statistical differences between the later ASD and TD groups were not reported in 3 studies.[45,61,64]

A meta-analysis of 7 studies involving children with later ASD and TD children revealed an overall large effect size of 1.14 (95% CI −1.48 to −0.81; $P < .001$) (Fig 5A), indicating poorer fine motor function in the later ASD group. There was evidence of substantial heterogeneity of the effect size (I^2 = 71%).

Gross Motor

Gross motor function of children with later ASD was examined in 6 studies by using the MSEL and VABS-II. In 5 studies,[42,43,55,62,63] the authors found that children with later ASD (mean age: 24 months) demonstrated poorer gross motor function in relation to TD children or normative data. Statistical difference between the later ASD and TD groups was not reported in one study.[64]

A meta-analysis of 4 studies involving children with later ASD and TD children revealed an overall large effect size of 1.47 (95% CI −1.74 to −1.21; $P < .001$) (Fig 5B), indicating poorer gross motor function in the later ASD group. There was evidence of insignificant heterogeneity of the effect size (I^2 = 0%).

Generalized Motor Function

Generalized motor function of children with later ASD was examined in 2 studies by using the BSFR and VABS-II. In both studies,[42,58] the authors reported that children with later ASD demonstrated poorer generalized motor function in relation to TD children.

A meta-analysis of 2 studies involving children with later ASD and TD children revealed an overall large effect size of 1.33 (95% CI −1.69 to −0.96; $P < .001$) (Fig 5C), indicating poorer generalized motor function in the later ASD group. There was evidence of substantial heterogeneity of the effect size (I^2 = 61%).

DISCUSSION

Our aim for this systematic review was to synthesize evidence of early motor functioning in children later diagnosed with NDD. Although the included studies documented early motor impairments among children later diagnosed with ADHD, ASD, DCD, FASD, and PDD-NOS, 84% (21 of 25) of the included studies in this review involved young children with later ASD. This limits our capacity to make inferences about the transdiagnostic nature of early motor impairments as an early marker of NDD risk. Accordingly, we focus the discussion on the findings of children with later ASD. Additional longitudinal studies with early motor assessments that are linked to later developmental functioning and diagnostic outcomes are essential to enable comparisons of early motor difficulties across different NDD groups.

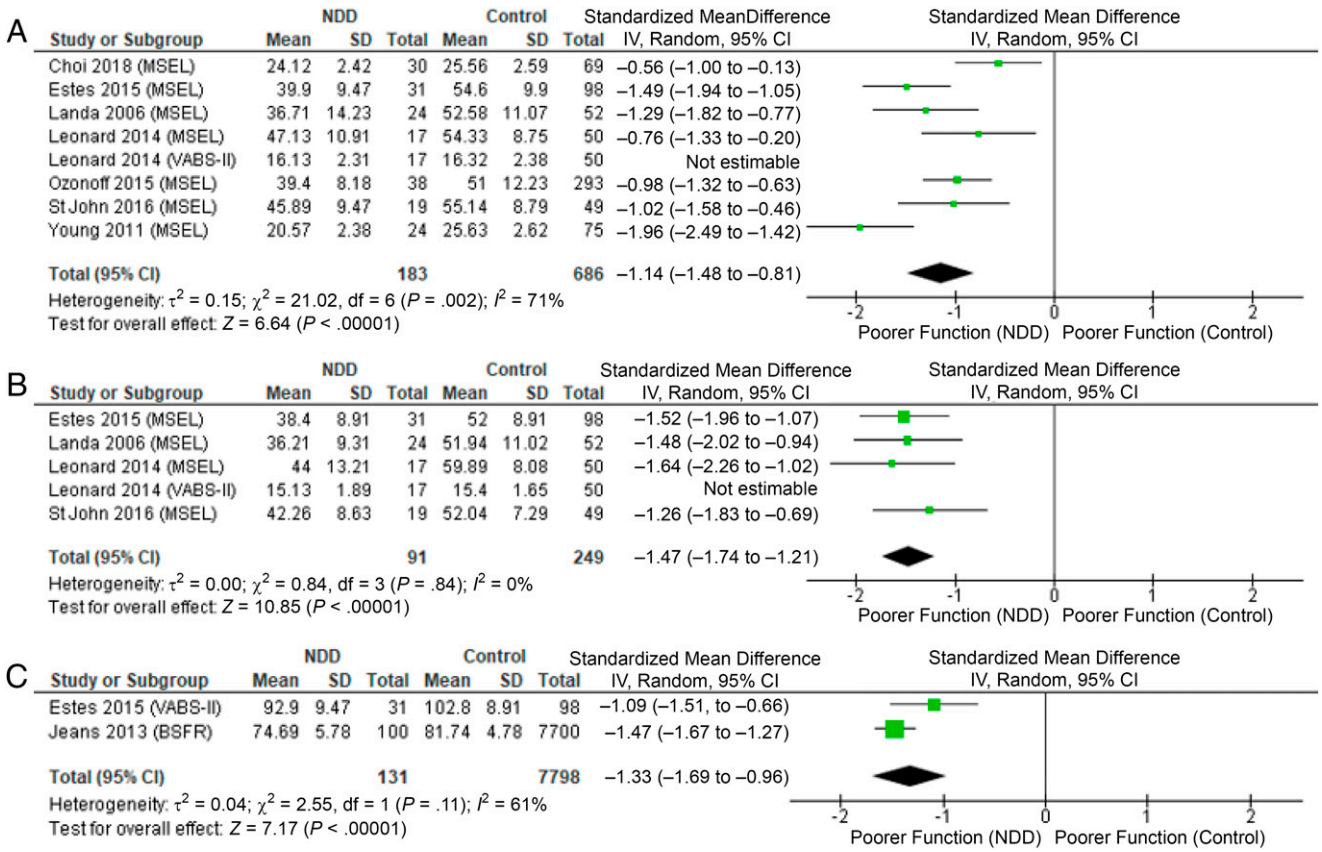

FIGURE 5

A–C, Forest plots of the comparison of fine motor function (A), gross motor function (B), and generalized motor function (C) in children (19–24 months) with later diagnoses of ASD versus controls. The motor function assessment used is indicated next to each study. df, degree of freedom; IV, inverse variance.

Consistent with previous findings of motor impairments in individuals with NDD,[65–68] we found that children with later ASD exhibited early impairments in fine, gross, and generalized motor functions. Our meta-analysis indicated that children with later ASD showed increasingly poorer motor function, compared with TD children, with increasing age. During early infancy (0–6 months), those with later ASD displayed small differences in fine and gross motor functions relative to TD children. By 19 to 24 months, large effect sizes were found across fine, gross, and generalized motor functions. These findings suggest that motor impairments can be detected in children from as early as 6 months, and thus these early motor impairments could be useful to identify children at risk for ASD. However, the predictive validity of early motor impairment should not be used alone and should be considered together with other markers of neurodevelopmental vulnerability, such as deviations in early speech and language development.[69]

An important consideration in developing strategies for the early identification of at-risk children is the selection of appropriate standardized motor function assessment tools for children between 0 and 24 months. In the present review, we identified 10 different types of standardized assessments that were used to measure motor function. The use of a variety of assessment tools to measure motor function is not uncommon. Spittle et al[70] found that across the 9 assessment tools used to measure motor development in preterm infants, all were appropriate for use, but each tool had a different purpose (ie, discriminative, predictive, or evaluative purposes). In the studies included in the current review, the MSEL was most frequently used. This is a practitioner-administered assessment that can be used on children from birth to 68 months.[71] Although the MSEL has been reported to have high interrater reliability (range: 0.91–0.99) and good construct and criterion validity in a normative population,[72] there is limited information regarding its sensitivity and specificity. More research on the psychometrics of the MSEL is needed to determine its appropriateness as a gold standard assessment tool for the measurement of motor function in

at-risk children between 0 and 24 months.

Only 3 of the 4 motor domains examined in the present review revealed early motor impairments in at-risk children. A large proportion of fine, gross, and generalized motor functions in young children with later ASD were found to be different from that of TD children; however, there were mixed findings in the general movement function. It is uncertain how the general movement function can provide meaningful information to detect motor impairments in at-risk children because only 3 included studies in the present review used the GMA to evaluate the general movement function. However, previous work has found support for the notion that GMA is a transdiagnostic measure of neurodevelopmental vulnerability. For example, among preterm infants, abnormal writhing general movements are associated later cognitive vulnerability.[73] Further research on the utility of the general movement function in the detection of early motor impairments in children later diagnosed with NDD is warranted.

In addition to the meta-analysis only comprising studies of children later diagnosed with ASD, this review has several limitations. First, a strict selection criterion was used to include studies in which motor function was only examined in children with later-diagnosed NDD. This led to many studies being excluded, for example, studies in which motor function was examined in at-risk children with no later diagnosis. In future work, researchers may wish to consider the association between early motor development and dimensional measures of later functioning, for example, cognitive development, or other transdiagnostic markers of neurodevelopmental vulnerability, such as dysregulated irritability.

Second, the current study contained only data from children with a later diagnosis of ADHD, ASD, DCD, FASD, and PDD-NOS; therefore, results may not be applicable to children with other types of NDD. Third, a wide range of heterogeneity was found in the meta-analyses; effect sizes with substantial and considerable heterogeneity should be interpreted with caution.

There is scope for research to further understand how early detection of motor impairments in children can be used as an early marker of ASD risk. In addition, the understanding of early motor impairment as a transdiagnostic marker of later NDD is currently limited by a paucity of studies on motor function in children later diagnosed with intellectual disability, language and speech disorder, ADHD, DCD, and FASD. Further studies in which motor function is examined in children across a wide range of NDD can be used to develop a comprehensive transdiagnostic profile of motor function in NDD. Given the heterogeneity in the clinical presentation of children with NDD, it is likely that motor profiles will be similarly heterogenous; however, transdiagnostic comparisons provide a basis for understanding latent classes of functioning that have important clinical implications.[74] In future work, researchers should also aim to determine best practice screening strategies for the early detection of motor impairments in children at risk for ASD and other NDD. This includes identifying appropriate assessment tools, standardized cutoffs for the classification of motor impairment, the recommended age for assessment, screening procedures, and cost.[75]

CONCLUSIONS

With the present systematic review, we provide evidence of early motor impairments in young children later diagnosed with ASD. With this review, we also provide mixed evidence of shared features of motor impairments across different types of NDD. Further work is needed to understand the clinical utility of motor impairment detection as a transdiagnostic early marker of NDD risk.

ABBREVIATIONS

ADHD: attention-deficit/hyperactivity disorder
ASD: autism spectrum disorder
ASQ-2: Ages and Stages Questionnaire, Second Edition
BSID-II: Bayley Scales of Infant Development, Second Edition
BSFR: Bayley Short Form Research Edition
CI: confidence interval
DCD: developmental coordination disorder
DDST: Denver Developmental Screening Test
FASD: fetal alcohol spectrum disorder
GMA: General Movements Assessment
GMDS-ER: Griffiths Mental Developmental Scales–Extended Revised
ICD-11: *International Classification of Diseases, 11th Revision*
KSPD: Kyoto Scale of Psychological Development
MSEL: Mullen Scales of Early Learning
NDD: neurodevelopmental disorders
PDD-NOS: pervasive developmental disorder not otherwise specified
PDMS-2: Peabody Developmental Motor Scales, Second Edition
TD: typically developing
VABS-II: Vineland Adaptive Behavior Scales, Second Edition

Dr Lim contributed to the conceptualization of the study, conducted the literature searches for the systematic review, reviewed articles for inclusion, performed data extraction, reviewed methodology of articles using the quality appraisal tool, analyzed the data, contributed to the interpretation of results, drafted the initial manuscript, and revised the manuscript; Drs Licari and Downs contributed to the conceptualization of the study, reviewed articles for inclusion, performed data extraction, reviewed methodology of articles using the quality appraisal tool, analyzed the data, contributed to the interpretation of results, and reviewed and revised the manuscript; Drs Spittle, Watkins, and Zwicker contributed to the conceptualization of the study, analyzed the data, contributed to the interpretation of results, and reviewed and revised the manuscript; Dr Finlay-Jones conceptualized and designed the study, reviewed articles for inclusion, performed data extraction, reviewed methodology of articles using the quality appraisal tool, analyzed the data, contributed to the interpretation of results, and reviewed and revised the manuscript; and all authors approved the final manuscript as submitted and agree to be accountable for all aspects of the work.

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