HHS Public Access

Author manuscript

Psychol Bull. Author manuscript; available in PMC 2023 February 02.

Published in final edited form as:

Psychol Bull. 2022 ; 148(3-4): 273–300. doi:10.1037/bul0000358.

Gross Motor Impairment and Its Relation to Social Skills in Autism Spectrum Disorder: A Systematic Review and Two Meta-Analyses

Leah A. L. Wang[1,2], **Victoria Petrulla**[3], **Casey J. Zampella**[1], **Rebecca Waller**[2], **Robert T. Schultz**[1,2,4,5]

[1]Center for Autism Research, The Children's Hospital of Philadelphia, Philadelphia, Pennsylvania, United States

[2]Department of Psychology, University of Pennsylvania

[3]Department of Psychology, Florida International University

[4]Department of Psychiatry, Perelman School of Medicine, University of Pennsylvania

[5]Department of Pediatrics, Perelman School of Medicine, University of Pennsylvania

Abstract

Gross motor ability is associated with profound differences in how children experience and interact with their social world. A rapidly growing literature on motor development in autism spectrum disorder (ASD) indicates that autistic individuals exhibit impairment in gross motor skills. However, due to substantial heterogeneity across studies, it remains unclear which gross motor skills are impaired in ASD, when and for whom these differences emerge, and whether motor and social impairments are related. The present article addressed these questions by synthesizing research on gross motor skills in ASD in two separate meta-analyses. The first examined gross motor deficits in ASD compared to neurotypical (NT) controls, aggregating data from 114 studies representing 6,423 autistic and 2,941 NT individuals. Results demonstrated a significant overall deficit in gross motor skills in ASD (Hedges' $g = -1.04$) that was robust to methodological and phenotypic variation and was significant at every level of the tested moderators. However, moderation analyses revealed that this deficit was most pronounced for object control skills (i.e., ball skills), clinical assessment measures, and movements of the upper extremities or the whole body. The second meta-analysis investigated whether gross motor and social skills are related in ASD, synthesizing data from 21 studies representing 654 autistic individuals. Findings revealed a modest but significant overall correlation between gross motor and social skills in ASD ($r = 0.27$). Collectively, results support the conclusion that motor deficits are tied to the core symptoms of ASD. Further research is needed to test the causality and directionality of this relationship.

Correspondence concerning this article should be addressed to Leah A. L. Wang, Department of Psychology, University of Pennsylvania, 425 South University Avenue, Philadelphia, PA 19104, United States. leahwang@sas.upenn.edu.

Supplemental materials: https://doi.org/10.1037/bul0000358.supp

Keywords

gross motor skills; social skills; autism; object control; meta-analysis

Motor skills are fundamental to human behavior and development. The empirical study of motor control was largely neglected by the field of psychology for decades (Rosenbaum, 2005). However, a recent resurgence of research in this area has established a robust link between gross motor and social communication skills. For example, in typically developing children, changes in posture and mobility are associated with changes in the social and communicative input that infants receive (Karasik et al., 2014; Kretch et al., 2014) and the social behaviors that they produce (Clearfield, 2011; Clearfield et al., 2008; Karasik et al., 2011). Similarly, poorer gross motor skills (i.e., motor skills involving movement of large muscle groups) have been shown to correlate with poorer interpersonal coordination (Fitzpatrick et al., 2017a, 2017b) and reduced participation in social activities (Bar-Haim & Bart, 2006; Jarus et al., 2011) in children and adolescents. Such evidence indicates that gross motor and social skills are intimately related, though the extent to which this relationship arises from direct causal influences between domains or shared underlying genetic or neural causes remains unknown.

For children on the autism spectrum,[1] motor deficits may compound existing vulnerabilities in the social domain (Leonard & Hill, 2014; West, 2019). Autism spectrum disorder (ASD) is a neurodevelopmental disorder characterized by core impairments in social communication and restricted and repetitive behaviors (American Psychiatric Association, 2013), affecting approximately one in 59 children in the United States (Baio et al., 2018). While motor impairment is not currently included in the diagnostic criteria for ASD, a growing body of literature supports the presence of pervasive gross motor abnormalities in ASD, including later achievement of early gross motor milestones (e.g., Liu, 2012), atypical gait (for a review, see Kindregan et al., 2015), more fragmented and less accurate reaching skills (Crippa et al., 2015; Yang et al., 2014), poor balance and postural instability (for a review, see Lim et al., 2017), difficulty with ball skills and object control (e.g., Ament et al., 2015), impaired coordination (e.g., Hilton et al., 2012), and poorer overall gross motor skills based on both parent report (e.g., Hedgecock et al., 2018) and clinical assessment (e.g., Pan, 2014). However, prior studies exhibit substantial heterogeneity in their construct of interest (e.g., gait, postural development, ball skills), method of measurement (e.g., standardized neuropsychological assessment, behavioral coding of video, kinematic motion capture), participant characteristics (e.g., age, sex), and level of statistical control for potentially confounding variables (e.g., intelligence quotient; IQ). Because of these inconsistencies, it is challenging to determine precisely which gross motor skills are impaired in ASD, the effect sizes of impairments for different types of gross motor skills, when in development these differences emerge, whether gross motor skill deficits are independent of broader cognitive or developmental functioning, or whether gross motor skill deficits are associated with specific subgroups or features of individuals on the autism spectrum.

[1]Identity-first language is used in this article rather than person-first language, consistent with preferences among autistic adults and self-advocates (Brown, 2011; Bury et al., 2020; Kenny et al., 2016).

A richer understanding of the nature of gross motor deficits in this population has important scientific and clinical implications. First, it may elucidate whether gross motor impairment should be considered a core feature of the autism phenotype. In recent years, as evidence has accumulated to support the presence of pervasive motor deficits in ASD, some researchers and clinicians have begun to call for motor impairment to be included in the diagnostic criteria or clinical specifiers for ASD (Bhat, 2020a, 2020b; Licari et al., 2020; Mosconi & Sweeney, 2015; Zampella et al., 2021), but questions remain regarding the pervasiveness and specificity of these impairments to ASD. Synthesizing the existing literature on gross motor impairment would help to determine which skills are impaired in ASD and assess the strength of their relationship to the core clinical features of ASD. Second, a fine-grained examination of the types of gross motor skills that are impaired in individuals on the autism spectrum may shed light on the specific motor processes that are disrupted in ASD. For instance, some studies have found that balance and object control skills (i.e., the ability to accurately and efficiently throw, strike, catch, and kick objects) are more impaired than other motor skills in ASD (Ament et al., 2015; Whyatt & Craig, 2012) and that object control skills are the only motor skills that predict later ASD symptom severity (MacDonald et al., 2013). As object control skills require continuous in-the-moment integration of sensorimotor feedback to adjust motor output, such findings provide novel hypotheses about the fundamental mechanisms underpinning motor impairment in ASD. Third, evidence from prospective studies suggests that deficits in gross motor skills are observable at 7 months of age in infants at high familial risk for ASD, earlier than any reliably observable social symptoms identified in the literature to date (Leonard et al., 2014). Gross motor skills have also been found to predict later social and communicative skills for autistic infants (West, 2019) and school-age children (MacDonald et al., 2013), even after controlling for other predictors, such as infant cognitive abilities. A better understanding of motor deficits in ASD would contribute to hypothesis generation surrounding potential predictors of ASD outcomes and targets for early intervention. For these reasons, a nuanced understanding of gross motor deficits and their relation to social skills in ASD has the potential to inform diagnosis, clinical intervention, phenotypic characterization, and knowledge of the etiology of ASD.

In service of this goal, meta-analysis can provide a comprehensive analysis of gross motor skill deficits and their association with social skill impairment in ASD by statistically synthesizing previous findings and testing the moderating effects of conceptual and methodological factors across studies. To date, three existing meta-analyses have addressed motor impairment in ASD. In 2010, Fournier, Hass, and colleagues published a meta-analysis examining motor coordination in ASD. The focus was not specifically on gross motor skills but did incorporate studies on coordination, gait, balance, and arm movements. Results demonstrated a robust difference in motor coordination skills in ASD (standardized mean difference; SMD effect size = 1.20). The authors examined several moderators of effect size but did not investigate the type of motor skill (e.g., balance, locomotion, ball skills) or cognitive ability as potential moderators. Since 2010, there has been a dramatic increase in the number of published studies of motor skills in ASD (Figure 1), meriting an updated meta-analysis of this literature. Lim et al. (2017) conducted a meta-analysis focused on standing postural control (i.e., ability to maintain stable upright posture while standing).

Autistic individuals exhibited significantly greater postural instability across a number of experimental conditions (effect sizes ranging from 0.87 to 1.85). These results provided fine-grained analysis of a single-skill area but did not resolve questions surrounding gross motor skills in ASD more broadly. Finally, a meta-analysis by West (2019) examined motor deficits in infants who went on to receive a diagnosis of ASD. Results demonstrated evidence of a significant overall motor skill deficit (effect size = 1.06) that was robust to variation in study design and methodology and increased across infancy, providing a more detailed picture of whether and when motor deficits emerge in early development for autistic individuals. However, included studies were confined to those of infancy and toddlerhood, and thus results cannot address whether motor impairments in ASD change over the lifespan. Moreover, this meta-analysis did not examine whether there are specific gross motor skills that are selectively more impaired among autistic individuals. Collectively, these prior meta-analyses leave unanswered questions about the specific types of gross motor skills that are impaired in ASD or whether any deficits are associated with, or better accounted for by, other phenotypic or methodological features. In addition, no prior meta-analysis has evaluated the relationship between gross motor and social skills among individuals on the autism spectrum.

Our meta-analysis focuses on gross motor skills rather than fine motor skills for both practical and theoretical reasons. First, gross motor skills hold particular promise as potential early predictors of ASD. As described above, there is a growing body of research demonstrating an association between motor and social skills in both typical and atypical development (Leonard & Hill, 2014; West, 2019). The majority of studies in this area focusing on infants and the early developmental period have identified close associations between changes in gross motor and social communication skills, with fewer focusing on fine motor behavior (Gonzalez et al., 2019; Leonard & Hill, 2014). Early gross motor milestones are highly observable and easy to reliably test and evaluate (WHO Multicentre Growth Reference Study Group, 2006), while fine motor behaviors are by contrast more refined, more difficult for observers to reliably characterize, and less salient to caregivers. Gross motor skills are more variable than fine motor skills very early in development (Leonard et al., 2015), due either to differences in ease of measurement early in life or true differences in maturation rate between domains; such interindividual variability is advantageous in that it may be predictive of individual differences in ASD-related behaviors and outcomes. Indeed, prior research has found that changes in gross but not fine motor skills in the first 7 months of life are associated with social communication development for typically developing infants (Libertus & Violi, 2016) and for infants who went on to receive a diagnosis of ASD (Leonard et al., 2015).

It was also necessary for our team to limit the scope of this meta-analysis in service of feasibility. Our literature searches were designed to capture all available research on motor and social skills in ASD—a literature that has exploded over the past decade (Figure 1). Ultimately, a combined total of over 300 articles were excluded at the abstract and full-text screening phases because they did not include a measure of gross motor skills, but may have measured another domain of motor behavior; indeed, we estimate that there are at least 120 full-text articles excluded from our meta-analysis that focus on fine motor skills specifically. In light of the scope of the literature on fine motor skills in ASD, a separate meta-analysis

focused on providing a detailed picture of fine motor behavior in ASD is warranted. Conducting separate meta-analyses of gross motor and fine motor skills in ASD would allow for more granular moderator analyses and clearer conclusions regarding the nature of motor impairment in ASD. In sum, given the literature supporting the association between gross motor and social development, preliminary evidence of a specific link between very early gross motor skills and later social communication outcomes, and practical constraints on the scope of our meta-analysis, we chose to focus our review on gross motor skills specifically.

Thus, the goal of the present study was to conduct a systematic review and two separate meta-analyses to synthesize knowledge about gross motor deficits and their relationship to social skills in autistic individuals. The first meta-analysis (Study 1) aggregated data and parsed heterogeneity across studies that had examined gross motor skills in ASD compared to neurotypical (NT) controls. Specifically, the aims of Study 1 were to (a) provide the most up-to-date estimate of the overall significance and effect size of gross motor deficits in ASD; (b) determine which aspects of gross motor ability are most or least impaired in autistic individuals relative to NT controls; and (c) investigate whether methodological differences (motor assessment modality, methodological quality) and phenotypic variables (age, IQ, sex) moderate these effects. The second meta-analysis (Study 2) synthesized data across studies that had examined the relationship between gross motor and social skill deficits in ASD.[2] The goals of this study were to (a) establish whether gross motor skill deficits are significantly associated with social skill deficits in ASD when aggregating across studies; (b) determine which specific domains of gross motor and social skills are associated; and (c) evaluate whether methodological differences (assessment modality, methodological quality) and phenotypic variables (age, IQ, sex) moderated these effects. Together, Study 1 provides the most comprehensive available understanding of how, when, and for whom gross motor skills are impaired in ASD and Study 2 elucidates the potential link between deficits in basic motor function and the core social symptoms of ASD.

Method

Search Procedure

A literature review was conducted in Pubmed and PsycINFO to identify studies on gross motor skills in ASD. In addition to keywords, to ensure discovery of all conceptually relevant findings (despite potential differences in specific terminology or keywords across articles), the controlled vocabulary of each database (Pubmed: Medical Subject Headings; PsycINFO: Thesaurus of Psychological Index Terms) was used to build searches. Searches required studies to have at least one motor-related classification (e.g., “motor skills,” “gait”) and at least one autism-related classification (e.g., “autism,” “autism spectrum disorder,” “Asperger syndrome,” “pervasive developmental disorder”[3]). In PsycINFO, search results

[2]Study 2 focuses only on individuals on the autism spectrum, as measures of social skills designed for autistic populations are typically not sensitive to individual differences in the NT range of skills, and thus likely to exhibit very little variability in NT samples. As a result, inclusion of NT groups could result in correlations that reflect categorical group differences rather than a continuous dimensional relationship between gross motor and social skills.

[3]“Asperger syndrome” and “pervasive developmental disorder” were included because Asperger syndrome and pervasive developmental disorder—not otherwise specified are considered disorders on the autism spectrum and were subsumed under the ASD diagnostic classification in the Diagnostic and Statistical Manual of Mental Disorders, 5th edition (American Psychiatric Association, 2013).

were restricted to studies with human subjects and studies in English. Subcategories of each controlled vocabulary term were evaluated and included where relevant, either by exploding the term or by selecting relevant individual subcategories to include in the search. No restrictions were placed on publication date. The full syntax for each search can be found in the Supplemental. Searches were carried out in March 2020 and identified both published and unpublished (i.e., dissertation) findings.

Collectively, after removing duplicate records, these database searches identified 1,085 unique articles. While screening full-text articles for eligibility, we identified 26 additional studies via backward searches of reference lists of included studies or previous meta-analyses for relevant articles that were not captured by our search. Of these, five remained in the final sample for Study 1, and one remained in the final sample for Study 2. The resulting 1,111 unique articles were subsequently screened for eligibility.

Study Screening and Selection Procedure

Abstract Screening—Articles were subjected to two rounds of screening (see Figure 2, for the flowchart summarizing screening procedures). First, two independent raters (Leah A. L. Wang and Victoria Petrulla) screened all 1,111 article abstracts using the open-source web application Rayyan (Ouzzani et al., 2016). Articles were screened for both Study 1 and Study 2 simultaneously and were excluded if ineligibility for both studies was apparent from the abstract alone (e.g., if the study did not include human subjects or did not include any reference to motor skills). Raters classified each abstract as either excluded or included for full-text screening and were blind to one another's ratings. Interrater reliability was high (Cohen's $\kappa = 0.72$, percent agreement = 87.70%). Conflicts were resolved via discussion. In total, 761 articles were excluded at this stage.

Study 1.: Articles were assessed for eligibility based on inclusion and exclusion criteria. For inclusion in Study 1, articles were required to incorporate all of the following: (a) human subjects and not solely a cellular, molecular, or animal model study; (b) a group of individuals with a confirmed diagnosis of ASD[4] (psychiatric comorbidities were permitted in the ASD group); (c) a NT control group, or data reported from an ASD group that could be compared to established population norms (i.e., standard scores from a norm-referenced measure of gross motor skills, age of gross motor milestone achievement); (d) a continuous measure of gross motor ability, defined as involving the action of large muscle groups (i.e., arms, legs, or torso), consistent with developmental theory, assessment, and research on motor development (Haibach-Beach et al., 2017); (e) at least 10 participants in both the ASD and NT groups, as very small studies would introduce more noise than signal into the data set and reduce power for detection of mean effect size (Hedges & Pigott, 2001)[5]; (f) original empirical data; (g) full-text availability in English; (h) a participant sample that did not overlap with other included articles, in order to ensure that the assumption of independence between studies was upheld[6]; and (i) data presented in a form that allowed for conversion to

[4]Studies on infants at high familial risk for ASD were not included unless they had a confirmed ASD diagnosis at outcome.
[5]The threshold of 10 participants was chosen a priori to mirror the existing meta-analysis of motor skills in autistic infants (West, 2019).
[6]If two studies included overlapping samples, the study with the larger number of participants in the ASD group was selected for inclusion. If overlap was suspected, but not explicitly stated, authors were contacted to determine whether samples were independent.

a SMD effect size (or the necessary data were able to be procured from the authors). Studies were excluded from Study 1 if they satisfied any of the following criteria: (a) an ASD group that consisted solely of participants with a genetic or neurological disorder known to affect motor function (e.g., Fragile X, Cerebral Palsy), as this would inflate effects; (b) only measures of fine motor skills, which was defined as precise movements of smaller muscles in the wrists, hands, or fingers (e.g., grasping, handwriting; Haibach-Beach et al., 2017); (c) only measures of atypical stereotyped movements or repetitive motor behaviors (as this meta-analysis did not aim to examine differences in motor behaviors that are included in the diagnostic criteria for ASD, which would be expected to differ between groups); (d) the article was solely a literature review or theoretical article.

Study 2.: Inclusion criteria for Study 2 were identical to Study 1, with the following exceptions: (a) the study was not required to include an NT group or to report a group difference in gross motor skills between autistic and NT individuals; (b) the study was required to report the bivariate correlation between a measure of gross motor skill and a measure of social skill *or* ASD social symptoms in a group of autistic individuals (or the necessary data were able to be procured from the authors).

Full-Text Screening—Following the abstract screening process, the full text of the remaining 350 articles was reviewed for eligibility for each study by two independent raters (Leah A. L. Wang and Victoria Petrulla). Conflicts were resolved via discussion and were arbitrated by an independent senior rater (Robert T. Schultz). If data provided in the study were insufficient for converting to the desired effect size (SMD effect size between an ASD group and an NT group for Study 1; the correlation between gross motor and social skills in an ASD group for Study 2), authors were contacted to request necessary data. This approach led to the inclusion of two additional articles in Study 1 after the authors provided the unpublished means and standard errors for a gross motor measure (Bremer & Cairney, 2018; Gowen & Miall, 2005). Four articles were included in Study 2 after the authors provided requested unpublished correlation data (Ament et al., 2015; Biffi et al., 2018; Ozonoff et al., 2008; Sacrey et al., 2018; World Health Organization, 2016). This stage yielded 114 studies that were eligible for inclusion in the Study 1 meta-analysis examining gross motor deficits in ASD and 21 studies that were eligible for inclusion in the Study 2 meta-analysis. See Figure 2 for the flowchart summarizing these steps.

Data Extraction and Coding Procedure

Data from all included studies were extracted into Microsoft Excel by two independent raters (Leah A. L. Wang and Victoria Petrulla). Conflicts were resolved via discussion and were arbitrated by an independent senior rater (Robert T. Schultz). where needed.

Study 1

Extracting Effect Sizes.: First, to compute effect sizes, sample sizes for the ASD and NT groups were extracted and the mean and standard deviation (*SD*) or standard error was

In the event that the authors did not respond, studies with similar authors and identical or almost identical phenotypic data (e.g., the same number of participants and mean age of participants in each group) were assumed to overlap.

extracted for each gross motor variable. For eight studies, means and standard deviations/errors were not reported in the article text but were available in a figure. In this case, data were extracted using the WebPlotDigitizer tool (Rohatgi, 2019) by two independent raters (Leah A. L. Wang and Victoria Petrulla), and values from each rater were averaged together. For nine studies, means and standard deviations/errors were not reported, but other statistics were reported that could be readily converted to a SMD effect (i.e., *t* value from an independent samples *t* test, *F* ratio from a one-way analysis of variance, Cohen's *d*). Extracted statistics were converted to Hedges' *g* effect sizes using formulas provided by Lipsey and Wilson (2001), implemented with the *esc* package in R (Version 0.5.1; Lüdecke, 2018). The direction of effects was coded such that negative Hedges' *g* values represent poorer or more atypical gross motor behavior in the ASD group.

Notably, a sizeable minority of the 114 included articles *(n* = 24) did not recruit an NT group but did report gross motor data that could be compared to established population norms. Previous meta-analyses of motor skills in ASD have excluded these studies (Fournier, Hass, et al., 2010; West, 2019); however, this decision has been critiqued, as norm-referenced measures are used frequently to study ASD and allow for comparison to large population-based samples rather than small, nonrandom samples of NT participants (Green, 2012). Instead of excluding these articles and eliminating valuable data from analysis, these articles were included and autistic participants' scores were compared to normative means and *SD*s for the measure (e.g., *M* = 100 and *SD* = 15 for scores on a standard scale). For these studies, effect size estimates and sampling variances were calculated using formulas for a one-sample mean (Borenstein et al., 2009).

Coding Moderator Data.: To address the aims of Study 1, conceptual, methodological, and phenotypic moderators were coded for each extracted effect. To test whether particular skills or muscle groups are selectively impaired in ASD, gross motor skill domain and muscle group were coded as categorical moderators. To investigate whether methodological factors influence effects, gross motor measurement modality was also coded as a categorical moderator. Furthermore, each study's methodological quality was rated and translated into a quality score, which was also analyzed as a continuous moderator (see below for details). Finally, the age, IQ, sex, and diagnostic subgroup were coded to test whether phenotypic factors are associated with gross motor deficits (see below for details).

Gross Motor Skill Domain.: Gross motor effects were coded into one of eight skill domains. Five categories were initially established a priori based on validated domains included in standardized assessments (Table S1), which themselves were derived via factor analysis. These initial categories were subsequently adapted after surveying and conceptually grouping studies that did not fit well into existing categories. Final categories used for data coding included locomotion, balance and posture, object control, motor control and coordination, imitation, reaching, strength and agility, and broad gross motor composite scores (see Table 1, for a detailed description of the skills encompassed by each category).

Muscle Group Involved in Gross Motor Skill.: Each effect was coded for the muscle groups recruited to perform the associated gross motor skill. Consistent with the prior meta-analysis of motor skills in ASD (Fournier, Hass, et al., 2010), muscle groups were coded as the upper

extremities, lower extremities, or whole body/combined upper and lower. However, unlike Fournier, Kimberg, et al. (2010), the present study classified measures involving balance in the whole body/combined upper and lower category, as the arms have been shown to play a role in maintaining an upright posture in addition to the legs and hips (Hill et al., 2019).

Gross Motor Measurement Modality.: Gross motor skills were coded into one of seven categories, established a priori based on currently available valid and reliable assessments of gross motor skills and knowledge of the field: (a) *clinical assessment* (use of a standardized observational assessment carried out by a clinician; e.g., the Movement Assessment Battery for Children); (b) *clinical interview* (use of a standardized clinician-administered parent interview; e.g., the Vineland Adaptive Behavior Scales); (c) *behavioral coding* (use of human raters to apply a coding scheme to video of motor behavior); (d) *parent questionnaire* (use of a self-administered parent-report measure; e.g., parent-reported age of child's motor milestone achievement); (e) *force and pressure* (use of force plates or pressure-sensitive gait carpets); (f) *kinematics* (use of video, motion-capture, or other objective methods to track movement in space and time); (g) *experimental tasks* (use of other experimental tasks that are not classified elsewhere; e.g., tracking force used to move a robotic arm).

Methodological Quality.: Methodological quality and risk of bias were rated for each included study by adapting items from the Cochrane risk of bias assessment tool (Higgins & Green, 2011). This tool is designed to capture features of studies that protect against bias in the collection, analysis, and reporting of results. To adapt this tool, items not relevant for noninterventional case-control studies were removed (e.g., blinding of participants to group assignment). Items were also added that were relevant for articles included in the present analysis: questions pertaining to ASD diagnosis (i.e., whether gold-standard diagnostic tools were used to confirm a diagnosis of ASD), peer review, and risk of bias in outcome variables (e.g., use of valid and reliable measures, whether measures relied solely on parent report). Two independent raters (Leah A. L. Wang and Victoria Petrulla) rated each study's quality and conflicts were resolved via discussion at the item level. Studies were not excluded on the basis of quality ratings; instead, ratings for each item were translated to a score of 0 or 1 and summed to produce a quality score for each study, which was subsequently examined as a continuous moderator of effects (a common approach for meta-analysis; Berman & Parker, 2002; Detsky et al., 1992; Luhmann & Eid, 2012). See Table 2 for a list of the questions included in the quality assessment, along with descriptive statistics on the consensus quality ratings for each item. Because our quality scale was tailored for the included studies and variables of interest, there is no validated threshold for what is considered an acceptable level of risk of bias. However, based on both the face validity of the items and the distribution of our quality ratings, a score of 13 or more for Study 1 (11 or more for Study 2) indicates below-average risk of bias (85th percentile or above), 10–12 (8–10 for Study 2) indicates an average risk of bias (25th–75th percentile), and below 10 (below 8 for Study 2) indicates above-average risk of bias (<25th percentile).

Autism Spectrum Disorder Diagnostic Group.: Prior to the publication of the 5th edition of the *Diagnostic and Statistical Manual for Mental Disorders* (DSM-5; APA, 2013), the broader umbrella of ASDs included several specific diagnostic categories, namely

autistic disorder, Asperger syndrome, and pervasive developmental disorder-not otherwise specified (PDD-NOS; American Psychiatric Association, 2000). Since the publication of the DSM-5, these diagnoses have been subsumed under the diagnostic classification of ASD. Many studies on gross motor skills published using the previous classification system included only a specific diagnostic subgroup. To investigate whether differences in gross motor deficits exist between subgroups, the diagnostic group of the participants associated with each effect was coded into one of four categories: (a) ASD (encompassing samples diagnosed with ASD per DSM 5/*International Statistical Classification of Diseases and Related Health Problems*, 10th edition (ICD-10; World Health Organization, 2016) criteria as well as samples that combined multiple DSM-IV diagnostic subgroups); (b) autistic disorder; (c) Asperger syndrome; or (d) PDD-NOS. If the article did not clearly state the participants' diagnostic labels, participants were classified in the ASD group.

Sex.: The percent of the ASD group that was male was extracted to be analyzed as a continuous moderator.

Age.: The mean chronological age of the ASD group was extracted to be analyzed as a continuous moderator. For longitudinal studies that collected data at predefined age intervals (e.g., at 12 months and 24 months), if mean age was not reported at each visit, the visit age was imputed for the mean age of the ASD sample (e.g., participants were assumed to be an average of 12 months old at the 12-month visit).

IQ.: The mean IQ of the ASD group was extracted to be analyzed as a continuous moderator. Cognitive assessments varied across studies, but IQ was only extracted if it was reported on a standard scale (i.e., mean of 100, *SD* of 15). Whenever possible, full-scale IQ (from Wechsler tests) or its equivalent (e.g., the General Conceptual Ability score from the Differential Ability Scales) was extracted. For the six studies that did not report full-scale IQ but did report a nonverbal IQ composite, nonverbal IQ was extracted. For two studies, only verbal IQ was reported. In these cases, IQ was not extracted, as many autistic individuals exhibit discrepancies between verbal and nonverbal IQ (Ankenman et al., 2014), and thus using them interchangeably is not appropriate.

Study 2

Extracting Effect Sizes.: To compute correlational effect sizes between gross motor and social measures, the sample size for the ASD group was extracted, along with every gross motor-social correlation coefficient (Pearson's r, Spearman's ρ, or Fisher's Z-transformed r) reported in the article. All extracted coefficients were then Fisher's Z transformed for meta-analysis if needed. Effects were coded such that positive correlations indicated that poorer gross motor skills were associated with poorer social skills.

Coding Moderator Data.: The same moderators coded for Study 1 were also coded for Study 2 (gross motor skill domain, gross motor measurement modality, muscle group, ASD subgroup, methodological quality, age, IQ, sex). Due to the smaller number of studies included in Study 2, conceptually related levels of complex moderators (e.g., clinical parent interview and parent questionnaires) were combined when necessary to ensure each level

had the sufficient number of studies for analysis (see the Results section, for details). In addition to the moderators described for Study 1, each effect for Study 2 was coded for three specific moderators related to the social skills variable: social skill domain, social skill measurement modality, and congruence between gross motor and social skill measurement modality.

Social Skill Domain.: Each correlational effect was coded for the type of social skill it represented. Categories were established a priori based on knowledge of the measures used in the field, and included (a) *social communication* (a measure of verbal and/or nonverbal communication skills in the context of social interaction; e.g., the Autism Diagnostic Observation Schedule [ADOS] Social Affect calibrated severity score); (b) *adaptive social skills* (a measure assessing everyday social functioning; i.e., the Vineland Adaptive Behavior Scales); (c) *social cognition* (the ability to perceive, understand, and apply social information; e.g., a theory of mind task); (d) *social motivation* (the tendency to seek out and find social interactions rewarding; e.g., the Social Responsiveness Scale–Social Motivation subscale); and (e) *broad social composite scores* (combining across different categories; e.g., the Bayley-III Socioemotional composite).

Social Skill Measurement Modality.: The method used to measure social skills was coded into one of six categories, which were established a priori. Categories include as follows: (a) clinical assessment (use of a standardized observational assessment carried out by a clinician; e.g., the ADOS); (b) *clinical interview* (use of a standardized clinician-administered parent interview; e.g., the Vineland Adaptive Behavior Scales); and (c) *parent or teacher report* (use of a self-administered parent- or teacher-report questionnaire; e.g., the Social Responsiveness Scale).[7]

Congruence Between Measurement Modalities.: In addition to coding the individual measurement modalities for gross motor and social variables, each correlation effect was coded according to whether the method of measurement was the same between the two. If both the gross motor and social variables were collected via the same modality (e.g., both parent report), the effect was coded as congruent; otherwise, it was coded as incongruent. Examining method congruence as a moderator allowed for examination of the extent to which correlational effects were attributable to common-method variance.

Handling Dependencies Between Effects—For 78% of articles in Study 1 and 90% of articles in Study 2, multiple relevant effects were reported, either due to longitudinal study design (e.g., repeating the same measure at multiple time-points), the use of multiple instruments to measure gross motor or social skills (e.g., two different parent questionnaires), or the inclusion of multiple independent samples (e.g., the same gross motor measure in a sample of autistic children and a sample of autistic adults). Rather than selecting a single effect to extract or aggregating all effects within studies, we extracted all relevant effects and implemented robust variance estimation (RVE) models, which are robust to assumptions about dependencies between effects (Hedges et al., 2010; see the

[7]One study contributed effects from a novel unstandardized task; this article was removed for the moderator analysis of social skill measurement modality, given the insufficient number of studies in this category.

"Statistical Approach" section). For standardized assessments, composite total scores were often presented alongside domain subscale scores. In these cases, data were extracted at the highest level that would preserve distinctions between levels of moderators considered in this meta-analysis. For example, if a study reported an overall gross motor quotient consisting of a balance subscale and object control subscale, we would extract the balance and control subscale scores rather than the overall quotient, since these represented distinct levels of the gross motor skill domain moderator. In contrast, if a locomotion composite was reported that included both walking and crawling subscales, the overall composite would be extracted since the walking and crawling subscales were not coded as different gross motor skills. If means and *SD*s of gross motor measures were presented separately according to moderators that were not addressed in the present study (e.g., autistic individuals with a developmental history of regression and those without), they were combined using standard formulas provided by Lipsey and Wilson (2001), and the associated sample characteristics were similarly combined. Finally, if gross motor skills were measured as pre/post outcome measures for an intervention study, only baseline effects were extracted for analysis.

Statistical Approach

Modeling Approach.: To include all relevant effects in our analyses, we implemented RVE metaregression models (Hedges et al., 2010). Conventional meta-analytic strategies rely on the assumption that studies report statistically independent effect sizes such that when studies report more than one effect, authors typically must either select a single effect to include (which may discard a substantial proportion of the available data and yield biased estimates) or construct a single synthetic effect for each study by combining dependent effects within studies. Accurately synthesizing dependent effects requires knowledge of their covariance structure. However, this information is rarely known, and traditional methods often combat this issue by making overly conservative approximations of covariance structures. In contrast to conventional methods, an RVE approach uses adjusted estimators for standard error that are robust to assumptions about the covariance between effects, allowing for inclusion of many dependent effects with unknown covariance structures. Given the high frequency of included studies that reported multiple relevant effects, and the substantial heterogeneity in the constructs and methods used to collect these effects across studies, the true covariance structure between effects was likely complex, but unknown. Therefore, RVE methods were deemed most appropriate for these data.

Outlier Detection.: To identify studies with undue influence and mitigate any issues surrounding the use of highly skewed moderators in RVE models, all effect sizes were examined for outliers. First, generalized extreme studentized deviate (GESD) tests were carried out to statistically identify outliers, with the maximum number of outliers set at 10% of the total number of effects (Rosner, 1983). Consistent with recommendations (Lipsey & Wilson, 2001), outlying effect sizes were winsorized by replacing them with the next closest value in the distribution. Because the GESD test assumes that the data (without outliers) are normally distributed, data were tested for normality using Shapiro–Wilk tests after outliers were winsorized. If the Shapiro–Wilk *W* statistic was less than 0.90 (indicative of nonnormally distributed data), the original values were reinstated, and subsequently only values that were more than three *SD*s above or below the mean value were winsorized.

Continuous moderators were tested for outliers using the GESD test (for normally distributed moderators) or by identifying values that are more than three *SD*s above or below the mean (for nonnormally distributed moderators). Sensitivity analyses were then carried out for each moderator in which metaregression was conducted with outlying moderator values included and with outlying moderator values winsorized. Results did not differ meaningfully in magnitude or significance when outlying values were winsorized; therefore, we present the results from the analyses including outlying moderator values.

Analytic Procedure.: For both Studies 1 and 2, we first ran an RVE metaregression model to estimate the relevant overall weighted-mean effect size (Study 1: Hedges' *g*; Study 2: Fisher's *Z*-transformed *r*). The overall model was a random-effects model with small-sample corrections (Tipton, 2015), clustering effects within studies and assuming a correlated dependence structure between effects, based on recommendations that meta-analysis select weights based on the type of dependence that is most prevalent in their data set (Tanner-Smith et al., 2016).[8]

Next, we examined the heterogeneity of effect sizes, as indicated by the I^2 statistic, an index of the percentage of variability in effect sizes that is not due to random sampling error (Higgins & Thompson, 2002). In the presence of substantial heterogeneity ($I^2 \geq 40\%$; Guyatt et al., 2011), separate planned univariate RVE models were carried out for each moderator. For categorical moderators, robust omnibus *F* tests with small-sample corrections were conducted to test the overall influence of the moderator on effect size; if the overall *F* test was significant, the significance of individual levels of the moderator and pairwise contrasts between levels of the moderator was examined by rotating the reference group in the categorical variable, with Bonferroni correction for multiple comparisons. Sensitivity analyses were conducted for all RVE models varying ρ from 0 to 1 in increments of 0.2; this did not change results for any reported analyses.

For continuous moderators, RVE and traditional metaregression models were carried out on the subset of articles with complete data for that moderator, since methods for imputing missing data have not yet been developed for RVE models. To test whether results were biased by missing moderator values, supplementary traditional metaregression models were run on data sets with missing values imputed via multiple imputation. Results are presented in the Supplemental (Table S4) and did not differ meaningfully from the traditional metaregression results on complete cases presented below.

All RVE analyses were carried out in R using the *robumeta* package (Version 2.0) for RVE metaregression models (Fisher & Tipton, 2014) and the *clubSandwich* package (Version 0.5.3) for robust *F* tests of categorical moderators (Pustejovsky, 2015). Effect sizes were aggregated for the traditional analyses using the *agg* function in the *MAd* (Version 0.8–2.1; Del Re & Hoyt, 2014) and *MAc* (Version 1.1.1; Del Re & Hoyt, 2010) packages for

[8]To ensure that analyses were robust to statistical method, traditional mixed-effects analyses were applied to aggregated effect sizes, calculating following the shifting-unit-of-analysis approach (Cooper, 2017). Across all analyses, results did not diverge meaningfully between the RVE and traditional mixed-effects models. Therefore, only the RVE results are presented. Results of the traditional mixed-effects models are available in the supplementary materials (Tables S2 and S3).

analysis of mean differences and correlations (respectively), and mixed-effects models were computed using the *metafor* package (Version 2.1–0; Viechtbauer, 2010).

Publication Bias.: We evaluated whether effect sizes were inflated by a lack of publication of small or nonsignificant effects. To visualize the distribution of effects at the study level, weighted-mean effect sizes were calculated for each study using formulas provided by Borenstein et al. (2009), assuming a correlation of $r = 0.80$ between effects within the same study.[9] A funnel plot was then generated from these study-level effects using the *meta* package in R (Version 4.11–0; Balduzzi et al., 2019) and was visually inspected for asymmetry. Funnel plots graph studies' effect sizes by their standard errors, and should be symmetrical if studies cluster appropriately around the overall aggregate effect size estimate; asymmetrical funnel plots are indicative of publication bias. In addition, the Egger sandwich test, an RVE-based adaptation of Egger's regression test (Rodgers & Pustejovsky, 2021), was run to statistically test for an association between standard error and effect size.

Transparency and Openness—Study data and *R* Markdown code used to analyze data and generate figures are publicly available at the following repository link: https://osf.io/ydrst/?view_only=207689671a1d46fab7c1260ad3923d4b. Tables containing important characteristics for articles included in Studies 1 and 2 (e.g., sample size, sample demographics, description of gross motor variables extracted) can be found in the supplement (Tables S9–S10). For articles from which multiple effects were extracted, these tables provide a broad summary of the extracted effects; descriptions of specific variables and extracted effect sizes can be found in the additional supplementary tables detailing individual article results (Tables S11–S12). Studies 1 and 2 and their associated statistical analysis plans were not preregistered.

Results

Study 1

Study Characteristics—In total, 114 studies were included in the meta-analysis on gross motor deficits in ASD, collectively representing 6,423 autistic and 2,941 NT individuals. Together, these 114 studies contributed 791 effects (*mdn* = 3, range = 1–48). The six studies that contributed more than 30 effects (Biffi et al., 2018; Kohen-Raz et al., 1992; Leezenbaum & Iverson, 2019; Liu, 2012; Morrison et al., 2018; Rinehart, Tonge, Bradshaw, et al., 2006) exhibited complex data structures and often reported several dependent gross motor variables in multiple conditions (e.g., eyes open, eyes closed) or effects from multiple independent autistic and NT groups (e.g., children, adolescents, and adults).

To protect against statistical issues of low power resulting from imbalanced categorical moderators, results of hypothesis tests in RVE moderator analyses were closely examined for small degrees of freedom. There were no instances in which results were significant but the degrees of freedom fell below 4. With respect to continuous moderators, 105 studies (92%) reported the mean chronological age of the autistic group. Among these studies, the

[9]Sensitivity analyses were carried out on publication results, varying the assumed correlation between effects from 0 to 1; results did not differ across values of *r*.

mean age in the autistic sample was 9.30 years (SD = 7.97 years; range = 6 months–49.7 years). The mean full-scale IQ in the autistic sample was reported in 64 studies (56%), and the overall mean IQ reported in these studies was 94.40 (SD = 13.53; range = 54.70–120.00). One hundred one studies (89%) reported the sex composition of the sample; the autistic samples in these studies were 81% male, on average (SD = 16.27%; range = 0%–100%). With regard to methodological quality, the mean total quality rating was 12.29 out of a possible total of 17 (SD = 1.90; range = 7–17).

Outlier Analysis—GESD tests identified 10 effect sizes ($g \leq -3.19$) as statistically significant outliers. These values were winsorized by replacing them with the next closest value in the distribution. Shapiro–Wilk tests confirmed that effect sizes were normally distributed after outliers were replaced (Ws > .90).

Overall Differences in Gross Motor Skills Between Neurotypical and Autistic Individuals—The first intercept-only RVE model tested whether autistic individuals exhibit overall gross motor deficits compared to NT individuals, incorporating all 114 studies and 791 effects. Model results revealed a large, significant mean effect size, Hedges' $g = -1.04$, $t(111) = -17.50$, $p < .0001$, 95% CI [−1.16, −0.92], reflecting substantial gross motor deficits for autistic individuals. The I^2 heterogeneity index for the overall model was 87.56, reflecting significant nonrandom heterogeneity across effects included in the model. Therefore, planned moderator analyses were carried out to investigate potential sources of heterogeneity. See Figure 3 for a forest plot of study-level aggregated effect sizes and their 95% confidence intervals.

Tests of Moderators of Gross Motor Impairment in ASD

Gross Motor Skill Domain.: The omnibus F test of the overall effect of gross motor skill domain was significant, $F(7, 29.88) = 7.58$, $p < .001$, indicating that the group difference effect differed significantly across domains. RVE results demonstrated that the overall effect size was significant for each individual skill domain (ps < .01), reflecting deficits across all domains for autistic participants. However, effect sizes for individual skill domains differed significantly in magnitude (Figure 4). Reaching was the least impaired skill ($g = -0.54$) and was significantly less impaired than object control, $g = -1.37$; $t(16.23) = 7.01$, $p < .001$, and balance and posture, $g = -0.95$; $t(9.33) = 4.72$, $p < .001$. Object control was most impaired ($g = -1.79$), and was significantly more impaired than balance and posture, $g = -0.95$; $t(31.34) = -3.69$, $p < .001$, in addition to reaching. No other contrasts between gross motor skill domains were significant. See Table 3 for the estimate of the overall Hedges' g in each skill domain.

Muscle Group Involved in Gross Motor Skill.: The omnibus F test of the overall effect of muscle group was significant, $F(2, 24.30) = 13.86$, $p < .001$), demonstrating that the effect size differed between muscle group categories. RVE results demonstrated that the overall effect size was significant for each individual muscle group (ps < .001), reflecting deficits in tasks involving every muscle group for autistic participants. However, muscle groups differed significantly in the magnitude of effect size (Figure 5). Tasks recruiting the lower extremities yielded a smaller group difference effect size ($g = -0.52$), on average, than tasks

recruiting either the upper extremities, $g = -0.94$; $t(17.00) = 3.58$, $p < .01$, or a combination of upper and lower extremities, $g = -1.11$; $t(11.30) = 5.30$, $p < .001$.

Gross Motor Measurement Modality.: The omnibus F test of the overall effect of gross motor measurement modality was significant, $F(6, 13.03) = 3.33$, $p = .03$, indicating that the group difference effect size differed significantly across modalities of measurement. Therefore, the reference category for the dummy variable was rotated and the significance of the intercept and pairwise contrasts between category levels was examined. Results demonstrated that the overall effect size was significant for each method of assessment (ps < .05), with each modality finding significant gross motor deficits in autistic individuals. However, effects differed significantly in magnitude between methods of assessment (Figure 6). Specifically, clinical assessment methods yielded significantly larger effect sizes ($g = -1.27$) than force and pressure, $g = -0.77$; $t(49.05) = -3.84$, $p < .001$, and kinematic, $g = -0.70$; $t(17.03) = -4.85$, $p < .001$, methods (Table 3).

ASD Diagnostic Group.: The omnibus F test of the overall effect of ASD diagnostic group was not significant, $F(3, 3.27) = 0.47$, $p = .72$, demonstrating that gross motor skill deficits are not associated with a particular diagnostic subgroup of individuals on the autism spectrum.

Methodological Quality.: Results indicated that methodological quality did not significantly predict effect size, $t(32.56) = -0.39$, $p = .70$.

Sex.: RVE model results indicated that sex composition did not significantly predict effect size, $t(9.19) = -0.74$, $p = .48$.

Age.: The RVE model found that age did not significantly predict effect size, $t(11.18) = 1.39$, $p = .19$.

IQ.: RVE model results demonstrated that IQ did not significantly predict effect size, $t(13.74) = 0.86$, $p = .40$.

Exploratory Analyses of Interactions Between Moderators—The planned moderator analyses indicated that gross motor skill domain, muscle group, and measurement modality significantly moderated the magnitude of gross motor impairments in autistic individuals relative to NT individuals. However, gross motor skill domains differed significantly on the basis of the method most commonly used to assess them (Table S5). Similarly, gross motor muscle groups also differed in method of assessment (Table S6). Because of this overlap, it was not clear from the planned analyses the extent to which the moderating effects of gross motor skill domain and gross motor muscle group were driven by differences in measurement method. For example, object control was the most significantly impaired skill domain, but all effects in this domain were derived using clinical assessment, the measurement modality that yielded the largest effects. Similarly, the lower extremities were found to be the least impaired muscle group, but no lower extremity effects were derived using clinical assessment.

In addition, muscle groups were not independent from skill domain. All the studies examining the lower extremities were studies of locomotion, while the majority of effects representing the whole body were measures of balance and posture, and the majority of effects representing the upper extremities assessed reaching skills (Table S7). The lower effect size observed in the lower extremities may, therefore, have been driven by the greater proportion of locomotion effects in the lower extremities relative to other muscle groups. To parse apart the unique effects of gross motor skill domain, muscle group, and measurement modality, exploratory RVE models were run on different subsets of data.

Gross Motor Skill Domain Versus Measurement Modality.: First, an RVE model was carried out examining the moderating effect of skill domain, including only effects derived from clinical assessment. This model included a total of 134 effects derived from a subset of 59 out of the original 114 studies. The estimated effect of object control ($g = -1.38$) was comparable to the effect from the overall model. Object control was found to be marginally significantly more impaired than balance and posture, $g = -1.14$; $t(30.64) = 2.03$, $p = .05$, 95% CI [−0.001, 0.48].[10] In contrast to the overall model, locomotion yielded a nonsignificantly higher overall effect than object control ($g = -1.50$). Therefore, the greater impairment in object control identified in the full sample relative to other domains may have been driven by the higher proportion of object control effects drawn from clinical assessment, but the effect size was nevertheless significant and comparable to the overall model.

Second, to test whether the greater effect sizes observed from clinical assessment were driven by impairment in object control, an RVE model was carried out examining the moderating effect of measurement modality, excluding object control effects. This model included a total of 761 effects out of the original 791 effects, derived from all 114 studies. Results demonstrated that clinical assessment still yielded the largest overall effect size ($g = -1.25$) that was comparable to the overall effect from the full model including object control effects and still significantly larger than effects derived from force and pressure, $g = -0.77$; $t(49.60) = 3.62$, $p < .001$, 95% CI [0.22, 0.75], and kinematic, $g = -0.70$; $t(17.07) = 4.57$, $p < .001$, 95% CI [0.30, 0.80], modalities after correcting for multiple comparisons. Thus, the finding that clinical assessment data are associated with larger effects was not driven by greater impairment in object control skills specifically.

Gross Motor Muscle Group Versus Measurement Modality.: Since clinical assessment was never used to assess the lower extremities (Table S6), an RVE model was carried out examining the moderating effect of muscle group, excluding effects derived from clinical assessment. This model included a total of 655 effects derived from a subset of 60 out of the original 114 studies. Tasks recruiting the lower extremities ($g = -0.52$) were still found to be significantly less impaired than tasks recruiting a combination of upper and lower extremities, $g = -0.85$; $t(13.82) = -3.11$, $p < .01$, 95% CI [−0.57, −0.10], and marginally significantly less impaired than tasks recruiting the upper extremities, $g = -0.69$; $t(19.17) = -1.88$, $p = .08$, 95% CI [−0.36, 0.02]. Therefore, the lesser impairment observed in the lower

[10] No comparison to reaching was possible, as reaching was never measured using standardized clinical assessments in the included studies.

extremities than other muscle groups may have been amplified, but not completely driven, by the lack of effects drawn from clinical assessment in the lower extremities.

Second, to test whether the smaller effects observed in the kinematic and force/pressure modalities compared to clinical assessment were driven by lesser impairment in the lower extremities, an RVE model was carried out examining the moderating effect of measurement modality, excluding lower extremity effects. This model included a total of 583 effects derived from a subset of 109 out of the original 114 studies. Results were consistent with results from the overall model. Clinical assessment still yielded the largest overall effect size ($g = -1.27$), which was significantly larger than effects derived from force and pressure, $g = -0.85$; $t(38.11) = 2.98$, $p < .01$, 95% CI [0.13, 0.70], kinematic, $g = -0.76$; $t(13.67) = 4.11$, $p < .01$, 95% CI [0.24, 0.78], parent questionnaire, $g = -0.55$; $t(4.65) = 4.55$, $p < .01$, 95% CI [0.30, 1.13], and experimental, $g = -0.75$; $t(3.44) = 3.42$, $p < .05$, 95% CI [0.07, 0.97], modalities. Thus, the finding that clinical assessment data are associated with larger effects than force/pressure or kinematic modalities was not driven by lesser impairment in the lower extremities.

Gross Motor Muscle Group Versus Skill Domain.: Because all the effects examining the lower extremities measured locomotion skills (Table S7), an RVE model was carried out examining the moderating effect of a muscle group, including only effects in the locomotion skill domain. This model included a total of 280 effects derived from a subset of 33 out of the original 114 studies. Tasks recruiting only the lower extremities ($g = -0.60$) were still found to be significantly less impaired than tasks recruiting a combination of upper and lower extremities, $g = -1.17$; $t(18.79) = -4.03$, $p < .001$, 95% CI [−0.98, −0.31]. Lower extremity effects did not differ significantly from upper extremity effects, $g = -1.50$; $t(1.62) = -3.09$, $p = .11$, 95% CI [−2.70, 0.74]; however, the lack of statistical significance was likely due to the low number of effects examining the upper extremities in the locomotion skill domain ($n = 10$), as the effect size for the upper extremities was even larger than the effect size for the combined upper and lower extremities. Thus, even within the locomotion skill domain alone, the lower extremities were less impaired than other muscle groups, indicating that the moderating effect of gross motor muscle group was not driven by an interaction with skill domain.[11]

Assessment for Publication Bias—Figure 7 shows the funnel plot of study-level aggregate effects. Visual inspection was not suggestive of significant plot asymmetry, and the Egger sandwich test was not significant, $t = 1.38$, $p = .18$, 95% CI [−0.73, 3.80]. Therefore, the findings included in Study 1 show no evidence of bias toward publication of larger effects, demonstrating that the overall effect estimate and moderator tests are robust to publication bias.

[11]Because skill domain analyses identified reaching as the least impaired skill domain, and reaching did not predominantly involve the lower extremities, we did not consider it necessary to test whether skill domain results were driven by differences between muscle groups.

Study 2

Study Characteristics—Twenty-one studies were included in the correlational meta-analysis for Study 2, contributing a total of 170 effects (*mdn* = 4, range = 1–44). Collectively, these studies provided data on the relationship between gross motor and social skills in a total of 654 autistic individuals. Several moderator levels were combined or excluded from analysis to avoid highly imbalanced moderators and ensure that each level had a sufficient number of studies for meaningful analysis (see Table S8, for the number of included studies and effects for each level of categorical moderators in Study 2). Only two studies used kinematic methods to assess motor behavior; these studies were combined with studies using force plates or pressure-sensitive gait mats to form an "objective measurement" category. The one study implementing a clinical parent interview to assess gross motor skills was combined with studies using parent-report questionnaires to form a "parent report" category. Levels of categorical moderators that could not be meaningfully combined with other levels and for which only one study contributed effects were excluded from moderator analysis; this included experimental tasks for both gross motor and social skill measurement modality; lower extremities for gross motor muscle group; and Asperger syndrome for ASD diagnostic subgroup. Finally, there were two moderator levels included in Study 1 that were not represented in any articles included in Study 2; specifically, no articles in Study 2 examined strength and agility or included a sample of participants with PDD-NOS. As in Study 1, to further address concerns surrounding low power resulting from imbalanced categorical moderators, hypothesis tests in RVE moderator analyses were closely examined for small degrees of freedom, and results were compared to traditional meta-analytic mixed-effects subgroup tests.

With respect to continuous moderators, 19 articles (90%) reported the mean chronological age of the autistic group. Among these articles, the mean age of the study sample was 6.81 years (*SD* = 5.28; range = 8 months–21.80 years). The mean full-scale IQ in the autistic sample was reported in 16 articles (76%), and the overall mean IQ reported in these articles was 93.11 (*SD* = 13.63; range = 54.70–109.50). Seventeen articles (81%) reported the sex composition of the sample, and the autistic samples in these articles were on average 88% male (*SD* = 9.61%; range = 60%–100%). The mean total quality rating across included articles was 9.95 out of a possible total of 13 (*SD* = 1.63; range = 7–12).

Outlier Analysis—A GESD test identified one effect size (Fisher's $Z = 1.42$) as a statistically significant outlier. This value was winsorized, and a Shapiro–Wilk test confirmed that the correlational effect sizes were normally distributed after this outlier was replaced ($W = 0.99$).

Overall Correlation Between Gross Motor and Social Skills—The intercept-only model representing the overall correlation between gross motor and social skills incorporating 21 studies and 170 effects demonstrated a modest and significant overall effect size of $r = 0.27$, Fisher's $Z = 0.28$, $t(18.80) = 5.78$, $p < .0001$, 95% CI [0.18–0.38], indicating that better gross motor skills are moderately associated with better social skills for people on the autism spectrum. The I^2 index for the overall model indicated that 60% of the total effect size variance was attributable to nonrandom heterogeneity across effects included

in the model. Planned moderator analyses were, therefore, carried out to investigate potential sources of heterogeneity. A forest plot of study-level aggregated effect sizes and their 95% confidence intervals is shown in Figure 8.

Tests of Moderators of the Relationship Between Gross Motor and Social Skills in ASD—None of the tested moderators were found to significantly moderate the correlation between gross motor and social skills in ASD. Statistical results are presented in Table 4.

Assessment for Publication Bias—Figure 9 shows the funnel plot of study-level aggregate effects. Both visual inspection and the Egger sandwich test, $t = 0.87$, $p = .42$, 95% CI [−0.81, 1.65], failed to find evidence of asymmetry, indicating that the findings included in Study 2 are robust to publication bias.

Discussion

Over the past 15 years, evidence has accumulated to support the presence of gross motor deficits for autistic individuals (Fournier, Hass, et al., 2010; Kindregan et al., 2015; Lim et al., 2017). However, critical gaps in knowledge remained about the effects of methodological differences on gross motor effect sizes, the specific types of gross motor skills that are impaired in ASD, and whether gross motor skills are more affected or more closely tied to social function for particular phenotypic groups within ASD. To address these questions, we conducted two comprehensive meta-analyses of findings pertaining to gross motor deficits and their relation to social skills in ASD. We found a large and robust gross motor impairment in ASD relative to NT development, adding to growing evidence of pervasive motor deficits among autistic individuals. We also demonstrated that gross motor skill type, muscle group, and measurement modality significantly moderate the magnitude of gross motor deficits in ASD, thereby expanding on existing findings to specifically identify which skills and measures are most affected in ASD. Furthermore, motor deficits were found to be significantly and modestly correlated with social deficits for individuals on the autism spectrum, indicating that gross motor impairment is associated with the core social deficits that characterize ASD. Taken together, our findings join a growing literature arguing for consideration of motor disturbance as a central feature of ASD (Bhat, 2020a, 2020b; Ketcheson et al., 2021; Licari et al., 2020; Mosconi & Sweeney, 2015).

Gross Motor Impairment in ASD

We integrated findings from 114 studies comparing gross motor ability between an autistic and NT control group and identified a large and highly significant overall group difference in gross motor skills in ASD, with autistic individuals differing from NT individuals by approximately one *SD* on average (Hedges' $g = -1.04$). The magnitude of this effect is comparable to the aggregate effects observed in previous meta-analyses focusing on motor coordination impairment in ASD (SMD = 1.20; Fournier, Hass, et al., 2010) and broad motor differences in autistic infants and toddlers (Hedges' $g = -1.06$; West, 2019). Even with our study's focus on gross motor impairment and its inclusion of 94 new studies compared to previous meta-analyses, the similarity in effect size supports the robust nature

of motor deficits in ASD. Crucially, we found that individuals on the autism spectrum displayed significant deficits in gross motor skills across each level of all investigated phenotypic and methodological moderators, demonstrating that autistic individuals exhibit pervasive and profound deficits in gross motor skills relative to their NT peers.

While autistic individuals displayed significant deficits in every domain of gross motor skill, moderator analyses found that the magnitude of impairment differed significantly between skill domains. The greatest deficits were in the object control domain ($g = -1.37$), which includes skills related to manipulating and moving objects (e.g., throwing, catching, and kicking). Compared to other skill domains, object control skills more often involve acting on moving objects, making them unique in their reliance on perception–action coupling—that is, the rapid use of complex sensory feedback to guide continuous, in-the-moment predictive adjustments to the timing and location of movements (Whyatt & Craig, 2013a). Our findings are consistent with prior research demonstrating that autistic individuals and infants at high risk for developing autism have difficulty using visual information to predictively guide movement (Landa et al., 2016; Whyatt & Craig, 2013b) and make more frequent compensatory adjustments to goal-directed movements (Forti et al., 2011).

This meta-analysis provides statistical evidence supporting the notion that perception–action coupling is a particularly critical area of disruption for autistic individuals and may be a fundamental feature of the autism phenotype. Viewed from a developmental perspective, this finding provokes numerous hypotheses about how perception–action coupling issues can specifically contribute to the development of the social problems that characterize ASD. For example, the ability to engage in appropriate and contingent interpersonal synchrony with others is fundamental to successful social interaction. However, deficits in perception–action coupling may make it more difficult for autistic individuals to coordinate their own motor behavior with the complex and hard-to-predict behavior of social partners. This hypothesis is supported by a growing literature demonstrating clear difficulties in the process of interpersonal coordination of autistic individuals (McNaughton & Redcay, 2020; Moody & McIntosh, 2006; Whyatt & Craig, 2013a; Zampella et al., 2020). For instance, effective social interaction requires individuals to perceive their social partner's verbal and nonverbal cues (e.g., prosody, syntax, gestures) and to use this perceptual information to guide and adapt their motor behavior and communication (e.g., to mirror their partner's body posture, nod along with their partner to express recognition and affiliation, or pause in response to their partner's facial expression). Indeed, evidence indicates that autistic individuals fail to use multisensory information to guide interpersonal motor coordination during a social interaction (Noel et al., 2017). Of note, meta-analysis indicates that automatic imitation of others' actions does not differ between autistic and NT individuals (Cracco et al., 2018); thus, it may be that only intentional, complex motor actions are affected.

In contrast, reaching was found to be the least impaired gross motor skill. Although reaching behavior differed significantly between autistic individuals and NT controls, the magnitude of the effect ($g = -0.54$) was smaller than all other gross motor domains, reflecting a moderate but robust impairment in the ability to accurately and effectively reach toward a goal. One possible explanation for the smaller effect size observed in this domain is that included studies predominantly employed tasks examining only a simple reach

toward a static, unmoving object. Simple goal-directed reaching tasks are less perceptually demanding, involving less sensorimotor integration and less complex motor planning and adaptation compared to other skill domains in our analyses. However, a growing literature indicates that autistic individuals have greater difficulty with complex, multistep reaching movements that rely on sensorimotor coupling to fine-tune motor plans (e.g., Crippa et al., 2015; Forti et al., 2011; Fukui et al., 2018; Sacrey et al., 2014; Yang et al., 2014). Thus, the majority of included studies may not have targeted the specific aspects of reaching that are most impaired in ASD. In addition, reaching was predominantly assessed using kinematic methods, and kinematic studies tended to collect and report many variables describing the spatial and temporal aspects of the reaching movement without making a priori hypotheses about which variables would be most likely to differ between groups. Given that no theoretical justification was provided for choosing one variable over another, all variables from kinematic studies were extracted for the current meta-analysis, and individual variables contributing large effects were aggregated with many variables contributing small effects. To test the extent to which reaching is truly less impaired in ASD, future research should select primary dependent variables measuring the aspects of the reaching movement that are most likely to differ between groups. Measures related to motor planning and adaptation during goal-directed movement, including movement speed, movement smoothness, and the presence of compensatory movement adjustments (e.g., number of movement units, total duration of reach, normalized jerk score) have been proposed as candidates for future investigation (Crippa et al., 2015; Forti et al., 2011; Sacrey et al., 2014); a systematic review or meta-analysis focused on an objective assessment of motor behavior in ASD would help to identify the variables that best discriminate between autistic and NT individuals.

In addition to gross motor skill domain, the modality of the gross motor assessment tool significantly moderated the magnitude of observed group differences in gross motor skill. Specifically, standardized clinical assessment produced significantly larger effects than both objective measures (i.e., force plates and kinematic motion capture) and parent-report questionnaires. While objective measures provide powerful methods for unbiased, granular assessment of motor behavior, as noted above, they require a priori feature selection in order to home in on the most meaningful differences between groups. In contrast, clinical assessment tools are specifically designed to elicit and capture only meaningful differences in motor behavior, which may have contributed to the larger effects found for clinical assessment. Moreover, standardized assessments are administered by clinicians who are trained to reliably observe and identify the specific aspects of motor behavior being tested. In contrast, parents observe their child’s behavior in the busy environment of everyday life rather than the focused context of clinical assessment and may not be as attuned to the aspects of motor behavior that are impaired in ASD. One alternative explanation for the greater effects observed for clinical assessment tools is that the majority of included studies that used clinical assessment did not attempt to blind clinicians to diagnostic status, which could have inflated effects if clinicians were biased to rate autistic children as more motor impaired purely on the basis of their diagnosis. Overall, however, despite some scatter in effects between modalities, every modality identified significant gross motor deficits in ASD.

Finally, the muscle group recruited to perform a gross motor skill was also found to significantly moderate effects, such that skills recruiting the lower extremities were significantly less impaired than skills recruiting the upper extremities or a combination of upper and lower extremities. This effect is somewhat surprising, given that Fournier, Kimberg, et al.'s (2010) meta-analysis of motor coordination impairment in ASD found that the upper extremities were the least impaired muscle group. Indeed, while the effect size is comparable between Fournier and colleagues' meta-analysis and the present analysis for the upper extremities (SMD = −0.88 vs. $g = -0.94$), we found the lower extremities to be less impaired (SMD = −1.12 vs. $g = -0.52$). Fournier and colleagues included a narrower range of motor skills, analyzed only one outcome measure per study, and assigned measures of balance to the lower extremities rather than to a combination of upper and lower extremities. Such differences in scope and methodology may have contributed to the discrepancy in the lower extremity effect size in our analyses. Nevertheless, our finding that skills recruiting the lower extremities are less impaired than skills recruiting the upper extremities in ASD warrants further discussion.

If autistic individuals truly have better control over their lower extremities than their upper extremities, this generates hypotheses surrounding the nature of the neurodevelopmental insults that give rise to gross motor deficits in ASD. One such hypothesis is that neural development of the white matter tracts supporting the upper extremities and trunk may be particularly disrupted in ASD. Alternatively, the smaller effect size observed in the lower extremities could reflect differences in the measures used to assess gross motor behavior across muscle groups. For example, the signal-to-noise ratio may be much lower in studies that measure movement in the lower extremities. The vast majority of these studies used kinematic, force, or pressure measures to assess movement during locomotion. As noted above, these studies tended to report all available variables, rather than making theory-driven hypotheses about which variables would be most likely to differ between groups, which could have washed out large effects. The type of gross motor skills represented in the lower extremity category may also exhibit ceiling effects, as all the studies examining the lower extremities were studies of gait and locomotion. In NT development, many gait measures rapidly and dramatically mature in the first 6 months of walking, after which development begins to asymptote (Adolph et al., 2003). Such nonlinear development may create a ceiling effect for these standard gait metrics for NT individuals later in life, lessening the gap between autistic and NT groups. Despite the smaller difference in performance on tasks that recruited the lower extremities alone, it is important to emphasize that autistic individuals were found to be significantly impaired in every muscle group, further supporting the pervasiveness of motor impairment in ASD.

Notably, gross motor skill domain, muscle group, and measurement modality were not independent variables. Some types of gross motor skills and certain muscle groups were much more frequently measured with one modality than with others. For example, reaching was predominantly measured using kinematics, while object control skills were measured only via clinical assessment. Furthermore, variability in task difficulty may have contributed to differences between skill domains. Object control measures assessed movement accuracy and possessed a high degree of task difficulty, while measures of goal-directed reaching most commonly assessed kinematic features of a highly stereotyped and well-rehearsed

movement. As described above, these methodological choices are important to consider when interpreting differences in the magnitude of impairment between specific types of gross motor skills or between muscle groups. Indeed, when examining only effects drawn from clinical assessments (which typically possess a high degree of task difficulty), object control skills were no longer significantly more impaired than other skill domains. With this in mind, researchers studying motor behavior in ASD should not only choose hypothesis-driven dependent variables but also carefully select the measurement modality that is best suited to capturing those variables. In addition, future work synthesizing findings related to motor performance in ASD should be sure to consider possible interactions between measurement choice and variables of interest.

Interestingly, no phenotypic variable studied significantly predicted the magnitude of gross motor deficits in ASD. The magnitude of gross motor deficits did not change according to chronological age, indicating that gross motor impairment is present from infancy and neither worsens nor remediates over the lifespan. This stands in contrast to the meta-analysis on motor skills conducted by West (2019), which found that motor deficits increase with age for autistic infants. However, this prior meta-analysis focused only on motor skills in the first 4 years of life, while the present analysis examined effects across the lifespan. Thus, it may be that the gap in gross motor skills between NT and autistic children widens from birth through early childhood and subsequently plateaus, remaining stable through adulthood. Indeed, supplementary analyses of the subset of articles included in the present meta-analysis that included children under the age of five found that gross motor deficits increased with age (see Supplemental). Importantly, the methodology used to study both ASD and motor behavior also changes with age, which may obscure real developmental changes in motor skills. For example, research evaluating motor behavior in infants and very young children is more likely to rely on clinical assessment and behavioral coding (in our sample, 70% of effects collected from children under 5 years of age used these methods), but rarely uses force and pressure, kinematics, or experimental methods (19% of effects collected from children under five). Given the variability in effect sizes across measurement modalities, this inconsistency in measurement method with age may have made it more difficult to capture true change in motor behavior over time. Moreover, because ASD cannot be reliably diagnosed until at least 14 months of age (Pierce et al., 2019) and the typical age of diagnosis is between 3 and 4 years of age (Maenner et al., 2020), researchers interested in studying early development in ASD typically either collect data retrospectively (e.g., analyzing archival home footage) or conduct prospective longitudinal studies of infants at high familial risk for ASD (i.e., with an older sibling with ASD). Retrospective methods are more prone to selection bias, while prospective infant sibling research yields small samples of children with ASD and only includes children in multiplex families (i.e., with more than one child with ASD); research on autistic individuals after the typical age of diagnosis is not faced with the same challenges or sources of bias. These unique methodological constraints on research on the early developmental period in ASD may have introduced noise into estimates of effect size for infants and young children, making it more difficult to capture meaningful trajectories of change in motor skills with age.

Cognitive ability was also not found to be a significant moderator of gross motor deficits, supporting the hypothesis that gross motor deficits are core phenotypic features of autism

rather than simply features of broader neurologic dysfunction or developmental delay. Finally, the sex composition of the participant sample was not found to moderate gross motor effects. However, articles were notably limited in the number of female participants included in analysis, warranting further investigation of sex differences in gross motor skills in ASD. Collectively, in the context of the growing debate over whether motor deficits should be considered core features of ASD (Fournier, Hass, et al., 2010; Rinehart & McGinley, 2010), the present findings indicate that individuals across the entire autism spectrum exhibit significant impairment in gross motor skills, supporting the notion that gross motor impairments are a core symptom of ASD. However, further research on the degree to which gross motor deficits interfere with daily functioning, as well as the specificity of gross motor deficits to ASD, is needed in order to determine whether motor deficits should be considered for inclusion as diagnostic criteria for ASD.

The Relation Between Gross Motor Skills and Social Skills in ASD

The meta-analysis of 21 studies that had reported a correlation between gross motor and social skills in autistic individuals found that poorer gross motor skills were moderately and significantly correlated with poorer social skills, with an overall correlation of $r = 0.27$. This relationship was significant across every level of the tested moderators, indicating that the association between gross motor and social deficits in ASD is robust across social skill domains, study methodology, and participant characteristics. Moreover, this correlation was not driven simply by common method variance, as effects were not significantly greater when gross motor and social skills were collected via the same measurement method. In addition, gross motor skill domain did not significantly moderate the effect, demonstrating that certain types of gross motor skills were not more strongly associated with social skills than other types. Thus, these findings suggest that gross motor deficits are significantly but perhaps only modestly tied to the core social symptoms of ASD.

It is important to note that the correlational effects included in this meta-analysis were all drawn from observational studies, most of which measured gross motor and social behavior concurrently. Thus, definitive conclusions regarding the directionality and causality of the relationship between gross motor and social skills cannot be drawn. However, existing literature provides several hypotheses for the potential mechanisms that could drive the association between gross motor and social skills in ASD. One possibility is that fundamental gross motor deficits in ASD could contribute to the development of social impairment over time by altering the ways in which autistic individuals perceive and interact with others. Early changes in posture and locomotion have been tied to changes in the social information that children see (Kretch et al., 2014) and the frequency and quality of their social interactions (Clearfield, 2011; Karasik et al., 2011, 2014), and may thereby alter children’s opportunities for social learning. Evidence suggests that difficulty with motor coordination may also affect the quality of social interaction for children, adolescents, and adults alike. For instance, deficits in basic motor skills may constrain interpersonal coordination of movements during social interaction (Bhat et al., 2011; Dowd et al., 2010; Moody & McIntosh, 2006). Problems using perceptual information to guide motor behavior, which the present findings suggest are particularly pronounced in ASD, may have an especially adverse effect on the ability to engage in interpersonal synchrony with social

partners, resulting in social interactions that are less fluid and sustained (Noel et al., 2017; Whyatt & Craig, 2013a). Motor impairment may also influence social development by reducing participation in social activities throughout the lifespan. For instance, school-age children with poorer motor coordination skills participate in fewer activities, engage in less social play, and choose more socially isolated activities than those with more advanced coordination skills (Bar-Haim & Bart, 2006; Jarus et al., 2011). Motor difficulties may continue to negatively impact social participation in adolescence, such that adolescents with a history of persistent motor difficulties participate in fewer social hobbies (Cantell et al., 1994). Notably, the converse relationship may also be true, such that social deficits contribute to the development of gross motor impairment. For NT children, many early gross motor actions are socially motivated or occur in a social context (e.g., walking toward parents to initiate an interaction, playing a reciprocal game of catch). Early social differences associated with ASD may limit children's participation in activities that would otherwise allow them to practice gross motor skills. Taken together, such findings suggest that gross motor coordination and social deficits may therefore have reciprocal cascading effects on one another throughout development. This interpretation implies that early gross motor impairment could compound preexisting social vulnerabilities for autistic children by impeding social learning and skill development over time.

Another possible explanation is that the association between gross motor and social deficits in ASD is the result of common neurobiological mechanisms (such that social deficits and motor deficits are expression of a common source), rather than direct causal effects of one domain on another. One possibility is that features of individual neurons or neural circuitry organization at local and/or global levels are shared across brain systems, serving as a developmental vulnerability for many different psychological and cognitive domains. The brain systems supporting motor and social behavior overlap (Barrett & Satpute, 2013; Van Overwalle, 2009, 2014), and the same insult could negatively affect functioning across both domains. Moreover, because neural systems mature at different rates early in development, the same neurobiological disruption may become manifest in one behavioral domain prior to another. In particular, the sensorimotor system matures before other functional brain systems (Gao et al., 2015), and thus the effects of the same underlying biological disturbance might be observable first in motor behavior and later in social behavior, with no causal relationship. Genetic differences can also exert changing levels of influence on behavior over time due to gene–environment correlation, as children select and modify their environment in ways that are consistent with their genetic predispositions (Plomin & Deary, 2015). This process of "genetic amplification" can lead the same underlying genetic differences to become increasingly phenotypically evident over time and may be observable first in the early-maturing motor domain and later in other behavioral domains. Therefore, even time-lagged correlations between early gross motor impairment and later social impairment may be caused by common underlying differences in genetics and brain function in ASD. Indeed, a twin study in the general population found evidence for a shared genetic influence between autistic traits and clumsiness (Moruzzi et al., 2011). Of course, these various explanations are not mutually exclusive and are likely to occur simultaneously. Further interventional and prospective longitudinal research is needed to disentangle the

directionality and causality of the relationship between gross motor and social skills and their relation to neural development in ASD.

Limitations

There are several limitations of the present analyses that warrant further discussion. First, it is unclear the degree to which gross motor deficits are specific to ASD. Only a handful of studies included a nontypically developing control group (e.g., attention-deficit/hyperactivity disorder, developmental delay, intellectual disability), which were too heterogeneous to meaningfully analyze. Thus, future studies are needed to compare autistic individuals to NT individuals, as well as comparison groups with other forms of neurodevelopmental disability, such as ADHD or language disorder. At the same time, it is notable that the motor skill domain found to be most impaired in the present analysis (object control) was also one of the only domains shown in one study to be selectively impaired in ASD compared to ADHD (Ament et al., 2015). Second, as described above, the correlational meta-analysis (Study 2) was dependent predominantly on cross-sectional observational studies, which does not allow for conclusions regarding the directionality, developmental timeline, or causality of the relationship between gross motor and social skills. Third, it is possible that the observed correlation between gross motor and social skills is a byproduct of Study 2's focus on autistic individuals alone. If both gross motor and social skills jointly contribute to the development of ASD symptoms (i.e., if ASD is a collider variable), their correlation in autistic individuals may be significant, even if such a correlation between motor and social communication ability does not exist in the general population. However, given that gross motor and social communication skills have been shown to be significantly correlated in typical development (Gonzalez et al., 2019; Leonard & Hill, 2014) and in population-based studies (Wang et al., 2014), it is unlikely that our results are driven solely by our focus on autistic individuals. Fourth, Study 2 was likely underpowered to detect moderator effects, given the smaller number of studies and imbalanced distribution of moderators (Hempel et al., 2013). As such, additional research will be needed to confirm whether the association between gross motor and social skills in ASD is truly independent of age, sex, and cognitive ability, and unrelated to skill domain or method of assessment. Fifth, the specificity of the relationship between gross motor and social skills remains unclear. Gross motor and social skills were selected for analysis for theoretical reasons, based on their relevance to ASD and existing evidence of their association in autistic and NT children. However, it may be that gross motor skills are equally or even more closely tied to skills in other areas of development (e.g., language, perceptual reasoning) that were not measured in the present study, or that fine motor skills are also associated with social skills. Future work disentangling the effects of gross motor skills on social skills from those of other skill domains will be important to elucidate the specificity of this relationship.

Conclusions

In sum, we provide the most comprehensive support to date for the existence of gross motor deficits in ASD and their robust association with social deficits for individuals on the autism spectrum. A number of important future directions can help to extend the current work and address the limitations described above. First, prospective longitudinal studies are needed

to investigate the directionality and temporal progression of the relationship between gross motor, social, and brain development in both typical development and ASD by collecting fine-grained, densely measured data on these variables in infants at high and low risk for ASD early in life. Second, our findings indicate that gross motor impairment is associated with the core social symptoms of ASD, and past research has indicated that gross motor deficits are detectable during the first year of life for children with ASD, prior to observable social symptoms (Estes et al., 2015; Lim et al., 2021; West, 2019). Future research is needed to investigate whether efforts to improve early prediction of later ASD outcomes might benefit from integrating measures of gross motor ability as an additional risk marker. Third, object control appears to be an area of particularly profound impairment for autistic individuals. Future research can help to elucidate whether this deficit is driven by difficulty with perception–action coupling (as hypothesized above), when it emerges in development, and whether it might serve as an early indicator of ASD outcomes. Perception–action coupling is especially relevant for social and affect coordination during social interactions (Zampella et al., 2020).

Our results hold several implications for clinical assessment and intervention. Research on motor impairment in ASD has identified a gap between the prevalence and diagnostic identification of clinically significant motor impairments in ASD, leading several researchers to call for routine evaluation of motor behavior for autistic individuals (Zampella et al., 2021). Our findings that gross motor impairment is pervasive and related to core social impairment for autistic individuals underscore the potential benefit of incorporating motor assessments into standard clinical evaluations for ASD. In addition to supporting clinicians' ability to identify and provide appropriate treatment recommendations for motor deficits in autistic individuals, motor assessments may supply clinicians with additional behavioral information that can improve the accuracy of their ASD diagnosis. Previous research has found that motor abnormalities, including awkward or uncoordinated movement, are frequently associated with a "frank" or "classic" presentation of ASD by experienced clinicians (de Marchena & Miller, 2017), suggesting that observation of motor behavior may help to inform clinicians' diagnostic impressions. Future research can investigate whether incorporating motor assessments into routine clinical practice improves diagnostic accuracy and later motor and social outcomes for people on the autism spectrum.

Finally, future studies can investigate gross motor skills and motor coordination as a putative target for intervention. To date, research on motor interventions for ASD have been plagued by small sample sizes and poorly controlled research designs; though large-scale, high-quality studies are needed in this area, it has not been clear what motor skills are the most important to target and which interventions are most important to study. Our findings identify object control as a skill that is especially impaired in ASD, highlighting it as a particularly important target for motor-focused interventions. A small number of preliminary research studies have developed and tested interventions targeting ball skills for autistic children (Bremer & Lloyd, 2016; Guest et al., 2017; Ketcheson et al., 2017); all found that not only did children's ball skills improve over the course of intervention, but their social participation (Ketcheson et al., 2017) and social skills (Bremer & Lloyd, 2016; Guest et al., 2017) did as well. Our results emphasize the importance of conducting future high-powered, well-controlled randomized intervention trials in this area.

In addition, our findings also suggest that gross motor skills may be fruitful targets for early intervention in ASD, an area that has not yet been explored. Such interventions could focus on providing children with increased opportunities for scaffolded learning and practicing gross motor skills. Notably, we did not find evidence that any one gross motor skill was more strongly tied to social communication skills; therefore, initial work in this area may focus on building developmentally appropriate skills across domains, including posture and locomotion (e.g., independent sitting, crawling, and walking), object control (e.g., rolling, throwing, and kicking), and goal-directed reaching. In light of the observed correlation between gross motor and social skills, it is possible that such early motor interventions may have downstream effects on social behavior for children on the autism spectrum. For this reason, we would encourage future motor intervention research to include social as well as motor outcome variables. Such intervention research could hold promise for not only supporting improved social outcomes for autistic individuals but also for moving beyond correlational research to experimentally test whether motor processes play a causal role in supporting social development for children on the autism spectrum.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

References

*Article included in Study 1. †Article included in Study 2.

Adolph KE, Vereijken B, & Shrout PE (2003). What changes in infant walking and why. Child Development, 74(2), 475–497. 10.1111/1467-8624.7402011 [PubMed: 12705568]

*†. Ament K, Mejia A, Buhlman R, Erklin S, Caffo B, Mostofsky S, & Wodka E (2015). Evidence for specificity of motor impairments in catching and balance in children with autism. Journal of Autism and Developmental Disorders, 45(3), 742–751. [PubMed: 25231287]

American Psychiatric Association. (2000). Diagnostic and statistical manual of mental disorders (4th ed., text rev.).

American Psychiatric Publishing American Psychiatric Association. (2013). Diagnostic and statistical manual of mental disorders: DSM-5 (5th ed.). American Psychiatric Publishing.

Ankenman K, Elgin J, Sullivan K, Vincent L, & Bernier R (2014). Nonverbal and verbal cognitive discrepancy profiles in autism spectrum disorders: Influence of age and gender. American Journal on Intellectual and Developmental Disabilities, 119(1), 84–99. 10.1352/1944-7558-119.1.84 [PubMed: 24450323]

*. Arabameri E, & Sotoodeh MS (2015). Early developmental delay in children with autism: A study from a developing country. Infant Behavior and Development, 39, 118–123. 10.1016/j.infbeh.2015.02.017 [PubMed: 25827390]

Baio J, Wiggins L, Christensen DL, Maenner MJ, Daniels J, Warren Z, Kurzius-Spencer M, Zahorodny W, Rosenberg CR, White T, Durkin MS, Imm P, Nikolaou L, Yeargin-Allsopp M, Lee LC, Harrington R, Lopez M, Fitzgerald RT, Hewitt A, … Dowling NF (2018). Prevalence of autism spectrum disorder among children aged 8 years—Autism and developmental disabilities monitoring network, 11 sites, United States, 2014. Morbidity and Mortality Weekly Report: Surveillance Summaries, 67(6), 1–23. 10.15585/mmwr.ss6706a1

Balduzzi S, Rücker G, & Schwarzer G (2019). How to perform a meta-analysis with R: A practical tutorial. Evidence-Based Mental Health, 22(4), 153–160. 10.1136/ebmental-2019-300117 [PubMed: 31563865]

Bar-Haim Y, & Bart O (2006). Motor function and social participation in kindergarten children. Social Development, 15(2), 296–310. 10.1111/j.1467-9507.2006.00342.x

Barrett LF, & Satpute AB (2013). Large-scale brain networks in affective and social neuroscience: Towards an integrative functional architecture of the brain. Current Opinion in Neurobiology, 23(3), 361–372. 10.1016/j.conb.2012.12.012 [PubMed: 23352202]

*. Bennetto L (1999). A Componential Analysis of Imitation and Movement Deficits in Autism. University of Denver.

*. Berkeley SL, Zittel LL, Pitney LV, & Nichols SE (2001). Locomotor and object control skills of children diagnosed with autism. Adapted Physical Activity Quarterly, 18(4), 405–416. 10.1123/apaq.18.4.405

Berman NG, & Parker RA (2002). Meta-analysis: Neither quick nor easy. BMC Medical Research Methodology, 2(10), Article 10. 10.1186/1471-2288-2-10 [PubMed: 12171604]

*. Bertilsson I, Gyllensten AL, Opheim A, Gard G, & Sjödahl Hammarlund C (2018). Understanding one's body and movements from the perspective of young adults with autism: A mixed-methods study. Research in Developmental Disabilities, 78(September 2017), 44–54. 10.1016/j.ridd.2018.05.002 [PubMed: 29772450]

Bhat AN (2020a). Is motor impairment in autism spectrum disorder distinct from developmental coordination disorder? A report from the SPARK study. Physical Therapy, 100(4), 633–644. 10.1093/ptj/pzz190 [PubMed: 32154876]

Bhat AN (2020b). Motor impairment increases in children with Autism Spectrum Disorder as a function of social communication, cognitive and functional impairment, repetitive behavior severity, and comorbid diagnoses: A SPARK study report. Autism Research, 14(1), 202–219. 10.1002/aur.2453 [PubMed: 33300285]

Bhat AN, Landa RJ, & Galloway JC (2011). Current perspectives on motor functioning in infants, children, and adults with autism spectrum disorders. Physical Therapy, 91(7), 1116–1129. 10.2522/ptj.20100294 [PubMed: 21546566]

*†. 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, Article 13. 10.3389/fpsyg.2018.02530 [PubMed: 29441028]

*. Biscaldi M, Rauh R, Irion L, Jung NH, Mall V, Fleischhaker C, & Klein C (2014). Deficits in motor abilities and developmental fractionation of imitation performance in high-functioning autism spectrum disorders. European Child & Adolescent Psychiatry, 23(7), 599–610. 10.1007/s00787-013-0475-x [PubMed: 24085467]

*†. Bojanek EK, Wang Z, White SP, & Mosconi MW (2020). Postural control processes during standing and step initiation in autism spectrum disorder. Journal of Neurodevelopmental Disorders, 12, Article 13. 10.1186/s11689-019-9305-x [PubMed: 32359368]

Borenstein M, Hedges LV, Higgins JPT, & Rothstein HR (2009). Introduction to meta-analysis. John Wiley and Sons. 10.1002/9780470743386

*†. Bremer E, & Cairney J (2018). The interrelationship between motor coordination and adaptive behavior in children with autism spectrum disorder. Frontiers in Psychology, 9, Article 7. 10.3389/fpsyg.2018.02350 [PubMed: 29449818]

Bremer E, & Lloyd M (2016). School-based fundamental-motor-skill intervention for children with autism-like characteristics: An exploratory study. Adapted Physical Activity Quarterly, 33(1), 66–88. 10.1123/APAQ.2015-0009 [PubMed: 26785501]

*. Breslin CM, & Rudisill ME (2011). The effect of visual supports on performance of the TGMD-2 for children with autism spectrum disorder. Adapted Physical Activity Quarterly, 28(4), 342–353. 10.1123/apaq.28.4.342 [PubMed: 21914906]

*. Brezis R-S, Noy L, Alony T, Gotlieb R, Cohen R, Golland Y, & Levit-Binnun N (2017). Patterns of joint improvisation in adults with autism spectrum disorder. Frontiers in Psychology, 8, Article 1790. 10.3389/fpsyg.2017.01790 [PubMed: 29114236]

Brown L (2011). Identity-first language. Retrieved May 5, 2020, from https://autisticadvocacy.org/about-asan/identity-first-language/

*. Bucci MP, Goulème N, Stordeur C, Acquaviva E, Scheid I, Lefebvre A, Gerard CL, Peyre H, & Delorme R (2017). Discriminant validity of spatial and temporal postural index in children with

neurodevelopmental disorders. International Journal of Developmental Neuroscience, 61(July), 51–57. 10.1016/j.ijdevneu.2017.06.010 [PubMed: 28684307]

Bury SM, Jellett R, Spoor JR, & Hedley D (2020). "It Defines Who I Am" or "It's Something I Have": What language do [Autistic] Australian adults [on the Autism Spectrum] prefer? Journal of Autism and Developmental Disorders. Advance online publication. 10.1007/s10803-020-04425-3

Cantell MH, Smyth MM, & Ahonen TP (1994). Clumsiness in adolescence: Educational, motor, and social outcomes of motor delay detected at 5 years. Adapted Physical Activity Quarterly, 11(2), 115–129. 10.1123/apaq.11.2.115

*. Chang CH, Wade MG, Stoffregen TA, Hsu CY, & Pan CY (2010). Visual tasks and postural sway in children with and without autism spectrum disorders. Research in Developmental Disabilities, 31(6), 1536–1542. 10.1016/j.ridd.2010.06.003 [PubMed: 20598853]

*. Chen FC, & Tsai CL (2016). A light fingertip touch reduces postural sway in children with autism spectrum disorders. Gait and Posture, 43, 137–140. 10.1016/j.gaitpost.2015.09.012 [PubMed: 26422366]

*. Chester VL, & Calhoun M (2012). Gait symmetry in children with autism. Autism Research and Treatment, 2012, Article 576478. 10.1155/2012/576478 [PubMed: 22934175]

*. Classen S, Monahan M, & Wang Y (2013). Driving characteristics of teens with attention deficit hyperactivity and autism spectrum disorder. The American Journal of Occupational Therapy, 67(6), 664–673. 10.5014/ajot.2013.008821 [PubMed: 24195900]

Clearfield MW (2011). Learning to walk changes infants' social interactions. Infant Behavior and Development, 34(1), 15–25. 10.1016/j.infbeh.2010.04.008 [PubMed: 20478619]

Clearfield MW, Osborne CN, & Mullen M (2008). Learning by looking: Infants' social looking behavior across the transition from crawling to walking. Journal of Experimental Child Psychology, 100(4), 297–307. 10.1016/j.jecp.2008.03.005 [PubMed: 18452944]

*. Cook JL, Blakemore SJ, & Press C (2013). Atypical basic movement kinematics in autism spectrum conditions. Brain: A Journal of Neurology, 136(Pt. 9), 2816–2824. 10.1093/brain/awt208 [PubMed: 23983031]

Cooper H (2017). Research synthesis and meta-analysis: A step-by-step approach (5th ed.). SAGE Publications. 10.4135/9781071878644

Cracco E, Bardi L, Desmet C, Genschow O, Rigoni D, De Coster L, Radkova I, Deschrijver E, & Brass M (2018). Automatic imitation: A meta-analysis. Psychological Bulletin, 144(5), 453–500. 10.1037/bul0000143 [PubMed: 29517262]

*†. Craig F, Lorenzo A, Lucarelli E, Russo L, Fanizza I, & Trabacca A (2018). Motor competency and social communication skills in preschool children with autism spectrum disorder. Autism Research, 11(6), 893–902. [PubMed: 29493892]

*. Crippa A, Salvatore C, Perego P, Forti S, Nobile M, Molteni M, & Castiglioni I (2015). Use of machine learning to identify children with autism and their motor abnormalities. Journal of Autism and Developmental Disorders, 45(7), 2146–2156. 10.1007/s10803-015-2379-8 [PubMed: 25652603]

de Marchena A, & Miller J (2017). "Frank" presentations as a novel research construct and element of diagnostic decision-making in autism spectrum disorder. Autism Research, 10(4), 653–662. 10.1002/aur.1706 [PubMed: 27770496]

Del Re AC, & Hoyt WT (2010). Meta-analysis with correlations [R package version 1.1.1]. https://cran.r-project.org/web/packages/MAc

Del Re AC, & Hoyt WT (2014). Meta-analysis with mean differences [R package version 0.8–2.1]. https://cran.r-project.org/web/packages/MAd

Detsky AS, Naylor CD, O'Rourke K, McGeer AJ, & L'Abbé KA (1992). Incorporating variations in the quality of individual randomized trials into meta-analysis. Journal of Clinical Epidemiology, 45(3), 255–265. 10.1016/0895-4356(92)90085-2 [PubMed: 1569422]

*. Doumas M, McKenna R, & Murphy B (2016). Postural control deficits in autism spectrum disorder: The role of sensory integration. Journal of Autism and Developmental Disorders, 46(3), 853–861. 10.1007/s10803-015-2621-4 [PubMed: 26446773]

Dowd A, Rinehart N, & McGinley J (2010). Motor function in children with autism: Why is this relevant to psychologists? Clinical Psychologist, 14(3), 90–96. 10.1080/13284207.2010.525532

*†. Dyck MJ, Piek JP, Hay D, Smith L, & Hallmayer J (2006). Are abilities abnormally interdependent in children with autism? Journal of Clinical Child and Adolescent Psychology, 35(1), 20–33. 10.1207/s15374424jccp3501_3 [PubMed: 16390300]

Emck C, Bosscher RJ, Van Wieringen PCW, Doreleijers T, & Beek PJ (2011). Gross motor performance and physical fitness in children with psychiatric disorders. Developmental Medicine and Child Neurology, 53(2), 150–155. 10.1111/j.1469-8749.2010.03806.x [PubMed: 20964672]

*. Esposito G, & Venuti P (2008). Analysis of toddlers' gait after six months of independent walking to identify autism: A preliminary study. Perceptual and Motor Skills, 106, 259–269. 10.2466/pms.106.1.259-269 [PubMed: 18459375]

*. Esposito G, Venuti P, Apicella F, & Muratori F (2011). Analysis of unsupported gait in toddlers with autism. Brain and Development, 33(5), 367–373. 10.1016/j.braindev.2010.07.006 [PubMed: 20708861]

*. Esposito G, Venuti P, Maestro S, & Muratori F (2009). An exploration of symmetry in early autism spectrum disorders: Analysis of lying. Brain & Development, 31(2), 131–138. 10.1016/j.braindev.2008.04.005 [PubMed: 18534798]

*. Estes A, Zwaigenbaum L, Gu H, St John T, Paterson S, Elison JT, Hazlett H, Botteron K, Dager SR, Schultz RT, Kostopoulos P, Evans A, Dawson G, Eliason J, Alvarez S, Piven J, & the IBIS network. (2015). Behavioral, cognitive, and adaptive development in infants with autism spectrum disorder in the first 2 years of life. Journal of Neurodevelopmental Disorders, 7(1), Article 24. 10.1186/s11689-015-9117-6 [PubMed: 26203305]

Fisher Z, & Tipton E (2014). Robumeta: Robust variance meta-regression [R package version 2.0]. https://arxiv.org/abs/1503.02220

†. Fitzpatrick P, Romero V, Amaral JL, Duncan A, Barnard H, Richardson MJ, & Schmidt RC (2017a). Social motor synchronization: Insights for understanding social behavior in autism. Journal of Autism and Developmental Disorders, 47(7), 2092–2107. 10.1007/s10803-017-3124-2 [PubMed: 28425022]

*. Fitzpatrick P, Romero V, Amaral JL, Duncan A, Barnard H, Richardson MJ, & Schmidt RC (2017b). Evaluating the importance of social motor synchronization and motor skill for understanding autism. Autism Research, 10(10), 1687–1699. 10.1002/aur.1808 [PubMed: 28590041]

*. Forti S, Valli A, Perego P, Nobile M, Crippa A, & Molteni M (2011). Motor planning and control in autism. A kinematic analysis of preschool children. Research in Autism Spectrum Disorders, 5(2), 834–842. 10.1016/j.rasd.2010.09.013

*. Fournier KA, Amano S, Radonovich KJ, Bleser TM, & Hass CJ (2014). Decreased dynamical complexity during quiet stance in children with autism spectrum disorders. Gait and Posture, 39(1), 420–423. 10.1016/j.gaitpost.2013.08.016 [PubMed: 24055002]

Fournier KA, Hass CJ, Naik SK, Lodha N, & Cauraugh JH (2010). Motor coordination in autism spectrum disorders: A synthesis and meta-analysis. Journal of Autism and Developmental Disorders, 40(10), 1227–1240. 10.1007/s10803-010-0981-3 [PubMed: 20195737]

*. Fournier KA, Kimberg CI, Radonovich KJ, Tillman MD, Chow JW, Lewis MH, Bodfishe JW, & Hass CJ (2010). Decreased static and dynamic postural control in children with autism spectrum disorders. Gait and Posture, 32(1), 6–9. 10.1016/j.gaitpost.2010.02.007 [PubMed: 20400311]

*. Freitag CM, Kleser C, Schneider M, & von Gontard A (2007). Quantitative assessment of neuromotor function in adolescents with high functioning autism and asperger syndrome. Journal of Autism and Developmental Disorders, 37(5), 948–959. 10.1007/s10803-006-0235-6 [PubMed: 17171541]

*. Fuentes CT, Mostofsky SH, & Bastian AJ (2009). Children with autism show specific handwriting impairments. Neurology, 73(19), 1532–1537. 10.1212/WNL.0b013e3181c0d48c [PubMed: 19901244]

*. Fuentes CT, Mostofsky SH, & Bastian AJ (2010). Perceptual reasoning predicts handwriting impairments in adolescents with autism. Neurology, 75(20), 1825–1829. 10.1212/WNL.0b013e3181fd633d [PubMed: 21079184]

*. Fukui T, Sano M, Tanaka A, Suzuki M, Kim S, Agarie H, Fukatsu R, Nishimaki K, Nakajima Y, & Wada M (2018). Older adolescents and young adults with autism spectrum disorder have difficulty chaining motor acts when performing prehension movements compared to typically

developing peers. Frontiers in Human Neuroscience, 12, Article 12. 10.3389/fnhum.2018.00430 [PubMed: 29406540]

*†. Fulceri F, Contaldo A, Parrini I, Calderoni S, Narzisi A, Tancredi R, Apicella F, & Muratori F (2015). Locomotion and grasping impairment in preschoolers with autism spectrum disorder. Clinical Neuropsychiatry, 12(4), 94–100.

*. Fulceri F, Tonacci A, Lucaferro A, Apicella F, Narzisi A, Vincenti G, Muratoria F, & Contaldo A (2018). Interpersonal motor coordination during joint actions in children with and without autism spectrum disorder: The role of motor information. Research in Developmental Disabilities, 80, 13–23. 10.1016/j.ridd.2018.05.018 [PubMed: 29879613]

*. Funahashi Y, Karashima C, & Hoshiyama M (2014). Compensatory postural sway while seated posture during tasks in children with autism spectrum disorder. Occupational Therapy International, 21(4), 166–175. 10.1002/oti.1375 [PubMed: 24956573]

Gao W, Alcauter S, Smith JK, Gilmore JH, & Lin W (2015). Development of human brain cortical network architecture during infancy. Brain Structure & Function, 220(2), 1173–1186. 10.1007/s00429-014-0710-3 [PubMed: 24469153]

*. Ghanouni P, Memari A-H, Gharibzadeh S, Eghlidi J, & Moshayedi P (2017). Effect of social stimuli on postural responses in individuals with autism spectrum disorder. Journal of Autism and Developmental Disorders, 47(5), 1305–1313. 10.1007/s10803-017-3032-5 [PubMed: 28236101]

Gonzalez SL, Alvarez V, & Nelson EL (2019). Do gross and fine motor skills differentially contribute to language outcomes? A systematic review. Frontiers in Psychology, 10, Article 2670. 10.3389/fpsyg.2019.02670 [PubMed: 31849775]

*. Gowen E, & Miall RC (2005). Behavioural aspects of cerebellar function in adults with Asperger syndrome. Cerebellum, 4(4), 279–289. 10.1080/14734220500355332 [PubMed: 16321884]

*†. Graham SA, Abbott AE, Nair A, Lincoln AJ, Müller R-A, & Goble DJ (2015). The influence of task difficulty and participant age on balance control in ASD. Journal of Autism and Developmental Disorders, 45(5), 1419–1427. 10.1007/s10803-014-2303-7 [PubMed: 25381191]

†. Green D, Baird G, Barnett AL, Henderson L, Huber J, & Henderson SE (2002). The severity and nature of motor impairment in Asperger's syndrome: A comparison with specific developmental disorder of motor function. Journal of Child Psychology and Psychiatry, and Allied Disciplines, 43(5), 655–668. 10.1111/1469-7610.00054 [PubMed: 12120861]

Green D (2012). Limitations of meta-analyses. Journal of Autism and Developmental Disorders, 42(8), 1774–1775. [PubMed: 22083783]

Guest L, Balogh R, Dogra S, & Lloyd M (2017). Examining the impact of a multi-sport camp for girls ages 8–11 with autism spectrum disorder. Therapeutic Recreation Journal, 51(2), 109–126. 10.18666/TRJ-2017-V51-I2-7383

Guyatt GH, Oxman AD, Kunz R, Woodcock J, Brozek J, Helfand M, Alonso-Coello P, Glasziou P, Jaeschke R, Akl EA, Norris S, Vist G, Dahm P, Shukla VK, Higgins J, Falck-Ytter Y, Schünemann HJ, Schünemann HJ, & the GRADE Working Group. (2011). GRADE guidelines: 7. Rating the quality of evidence—inconsistency. Journal of Clinical Epidemiology, 64(12), 1294–1302. 10.1016/j.jclinepi.2011.03.017 [PubMed: 21803546]

Haibach-Beach PS, Reid G, & Collier DH (2017). Motor learning and development (2nd ed.). Human Kinetics.

*. Hanaie R, Mohri I, Kagitani-Shimono K, Tachibana M, Matsuzaki J, Hirata I, Nagatani F, Watanabe Y, Fujita N, & Taniike M (2016). White matter volume in the brainstem and inferior parietal lobule is related to motor performance in children with autism spectrum disorder: A voxel-based morphometry study. Autism Research, 9(9), 981–992. 10.1002/aur.1605 [PubMed: 26808675]

*. Hannant P (2018). Receptive language is associated with visual perception in typically developing children and sensorimotor skills in autism spectrum conditions. Human Movement Science, 58, 297–306. 10.1016/j.humov.2018.03.005 [PubMed: 29549746]

*. Hasan CZC, Jailani R, Md Tahir N, & Ilias S (2017). The analysis of three-dimensional ground reaction forces during gait in children with autism spectrum disorders. Research in Developmental Disabilities, 66, 55–63. 10.1016/j.ridd.2017.02.015 [PubMed: 28284567]

*. Hauck JA, & Dewey D (2001). Hand preference and motor functioning in children with autism. Journal of Autism and Developmental Disorders, 31(3), 265–277. 10.1023/A:1010791118978 [PubMed: 11518481]

*. Hedgecock JB, Dannemiller LA, Shui AM, Rapport MJ, & Katz T (2018). Associations of gross motor delay, behavior, and quality of life in young children with autism spectrum disorder. Physical Therapy, 98(4), 251–259. 10.1093/ptj/pzy006 [PubMed: 29325143]

Hedges LV, & Pigott TD (2001). The power of statistical tests in meta-analysis. Psychological Methods, 6(3), 203–217. 10.1037/1082-989X.6.3.203 [PubMed: 11570228]

Hedges LV, Tipton E, & Johnson MC (2010). Robust variance estimation in meta-regression with dependent effect size estimates. Research Synthesis Methods, 1(1), 39–65. 10.1002/jrsm.5 [PubMed: 26056092]

Hempel S, Miles JN, Booth MJ, Wang Z, Morton SC, & Shekelle PG (2013). Risk of bias: A simulation study of power to detect study-level moderator effects in meta-analysis. Systematic Reviews, 2(1), Article 107. 10.1186/2046-4053-2-107 [PubMed: 24286208]

Higgins JPT, & Green S (Eds.). (2011). Cochrane handbook for systematic reviews of interventions version 5.1.0. The Cochrane Collaboration.

Higgins JPT, & Thompson SG (2002). Quantifying heterogeneity in a meta-analysis. Statistics in Medicine, 21(11), 1539–1558. 10.1002/sim.1186 [PubMed: 12111919]

Hill MW, Wdowski MM, Pennell A, Stodden DF, & Duncan MJ (2019). Dynamic postural control in children: Do the arms lend the legs a helping hand? Frontiers in Physiology, 9(January), Article 1932. 10.3389/fphys.2018.01932 [PubMed: 30705636]

*. Hilton CL, Zhang Y, Whilte MR, Klohr CL, & Constantino J (2012). Motor impairment in sibling pairs concordant and discordant for autism spectrum disorders. Autism: An International Journal of Research and Practise, 16(4), 430–441. 10.1177/1362361311423018

*†. Hirata S, Okuzumi H, Kitajima Y, Hosobuchi T, Nakai A, & Kokubun M (2014). Relationship between motor skill and social impairment in children with autism spectrum disorders. International Journal of Developmental Disabilities, 60(4), 251–256. 10.1179/2047387713Y.0000000033

*†. Holloway JM, Long TM, & Biasini F (2018). Relationships between gross motor skills and social function in young boys with autism spectrum disorder. Pediatric Physical Therapy, 30(3), 184–190. 10.1097/PEP.0000000000000505. [PubMed: 29727358]

*. Iverson JM, Shic F, Wall CA, Chawarska K, Curtin S, Estes A, Gardner JM, Hutman T, Landa RJ, Levin AR, Libertus K, Messinger DS, Nelson CA, Ozonoff S, Sacrey L-AR, Sheperd K, Stone WL, Tager-Flusberg HB, Wolff JJ, … Young GS (2019). Early motor abilities in infants at heightened versus low risk for ASD: A baby siblings research consortium (BSRC) study. Journal of Abnormal Psychology, 128(1), 69–80. 10.1037/abn0000390 [PubMed: 30628809]

*. Jansiewicz EM, Goldberg MC, Newschaffer CJ, Denckla MB, Landa R, & Mostofsky SH (2006). Motor signs distinguish children with high functioning autism and Asperger's syndrome from controls. Journal of Autism and Developmental Disorders, 36(5), 613–621. 10.1007/s10803-006-0109-y [PubMed: 16609826]

Jarus T, Lourie-Gelberg Y, Engel-Yeger B, & Bart O (2011). Participation patterns of school-aged children with and without DCD. Research in Developmental Disabilities, 32(4), 1323–1331. 10.1016/j.ridd.2011.01.033 [PubMed: 21324639]

*. Jasmin E, Couture M, McKinley P, Reid G, Fombonne E, & Gisel E (2009). Sensori-motor and daily living skills of preschool children with autism spectrum disorders. Journal of Autism and Developmental Disorders, 39(2), 231–241. 10.1007/s10803-008-0617-z [PubMed: 18629623]

*. Jones V, & Prior M (1985). Motor imitation abilities and neurological signs in autistic children. Journal of Autism and Developmental Disorders, 15(1), 37–46. 10.1007/BF01837897 [PubMed: 3980428]

Karasik LB, Tamis-Lemonda CS, & Adolph KE (2014). Crawling and walking infants elicit different verbal responses from mothers. Developmental Science, 17(3), 388–395. 10.1111/desc.12129 [PubMed: 24314018]

Karasik LB, Tamis-LeMonda CS, & Adolph KE (2011). Transition from crawling to walking and infants' actions with objects and people. Child Development, 82(4), 1199–1209. 10.1111/j.1467-8624.2011.01595.x [PubMed: 21545581]

†. Kaur M, Srinivasan SM, & Bhat AN (2018). Comparing motor performance, praxis, coordination, and interpersonal synchrony between children with and without autism spectrum disorder (ASD). Research in Developmental Disabilities, 72(October 2017), 79–95. 10.1016/j.ridd.2017.10.025 [PubMed: 29121516]

Kenny L, Hattersley C, Molins B, Buckley C, Povey C, & Pellicano E (2016). Which terms should be used to describe autism? Perspectives from the UK autism community. Autism: An International Journal of Research and Practise, 20(4), 442–462. 10.1177/1362361315588200

Ketcheson L, Hauck J, & Ulrich D (2017). The effects of an early motor skill intervention on motor skills, levels of physical activity, and socialization in young children with autism spectrum disorder: A pilot study. Autism: An International Journal of Research and Practise, 21(4), 481–492. 10.1177/1362361316650611

Ketcheson LR, Pitchford EA, & Wentz CF (2021). The relationship between developmental coordination disorder and concurrent deficits in social communication and repetitive behaviors among children with autism spectrum disorder. Autism Research, 14(4), 804–816. 10.1002/aur.2469 [PubMed: 33421296]

*†. Kim H, Carlson AG, Curby TW, & Winsler A (2016). Relations among motor, social, and cognitive skills in pre-kindergarten children with developmental disabilities. Research in Developmental Disabilities, 53–54, 43–60. 10.1016/j.ridd.2016.01.016 [PubMed: 26540297]

Kindregan D, Gallagher L, & Gormley J (2015). Gait deviations in children with autism spectrum disorders: A review. Autism Research and Treatment, 2015, Article 741480. 10.1155/2015/741480 [PubMed: 25922766]

*. Kohen-Raz R, Volkmar FR, & Cohen DJ (1992). Postural control in children with autism. Journal of Autism and Developmental Disorders, 22(3), 419–432. 10.1007/BF01048244 [PubMed: 1383190]

*. 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. 10.1016/j.ridd.2009.09.017 [PubMed: 19910158]

Kretch KS, Franchak JM, & Adolph KE (2014). Crawling and walking infants see the world differently. Child Development, 85(4), 1503–1518. 10.1111/cdev.12206 [PubMed: 24341362]

*. Landa R, & Garrett-Mayer E (2006). Development in infants with autism spectrum disorders: A prospective study. Journal of Child Psychology and Psychiatry, and Allied Disciplines, 47(6), 629–638. 10.1111/j.1469-7610.2006.01531.x [PubMed: 16712640]

Landa RJ, Haworth JL, & Nebel MB (2016). Ready, set, go! Low anticipatory response during a dyadic task in infants at high familial risk for autism. Frontiers in Psychology, 7, Article 721. 10.3389/fpsyg.2016.00721 [PubMed: 27252667]

*†. Lane A, Harpster K, & Heathcock J (2012). Motor characteristics of young children referred for possible autism spectrum disorder. Pediatric Physical Therapy, 24(1), 21–29. 10.1097/PEP.0b013e31823e071a [PubMed: 22207461]

*. LeBarton ES, & Landa RJ (2019). Infant motor skill predicts later expressive language and autism spectrum disorder diagnosis. Infant Behavior and Development, 54(November 2018), 37–47. 10.1016/j.infbeh.2018.11.003 [PubMed: 30557704]

*. Leezenbaum NB, & Iverson JM (2019). Trajectories of posture development in infants with and without familial risk for autism spectrum disorder. Journal of Autism and Developmental Disorders, 49(8), 3257–3277. 10.1007/s10803-019-04048-3 [PubMed: 31079276]

Leonard HC, Bedford R, Pickles A, & Hill EL (2015). Predicting the rate of language development from early motor skills in at-risk infants who develop autism spectrum disorder. Research in Autism Spectrum Disorders, 13–14, 15–24. 10.1016/j.rasd.2014.12.012

*. Leonard HC, Elsabbagh M, & Hill EL (2014). Early and persistent motor difficulties in infants at-risk of developing autism spectrum disorder: A prospective study. European Journal of Developmental Psychology, 11(1), 18–35. 10.1080/17405629.2013.801626

Leonard HC, & Hill EL (2014). Review: The impact of motor development on typical and atypical social cognition and language: A systematic review. Child and Adolescent Mental Health, 19(3), 163–170. 10.1111/camh.12055 [PubMed: 32878369]

*. Li Y, Mache MA, & Todd TA (2019). Complexity of center of pressure in postural control for children with autism spectrum disorders was partially compromised. Journal of Applied Biomechanics, 35(3), 190–195. 10.1123/jab.2018-0042 [PubMed: 30676165]

Libertus K, Sheperd KA, Ross SW, & Landa RJ (2014). Limited fine motor and grasping skills in 6-month-old infants at high risk for autism. Child Development, 85(6), 2218–2231. 10.1111/cdev.12262 [PubMed: 24978128]

Libertus K, & Violi DA (2016). Sit to talk: Relation between Motor Skills and Language Development in Infancy. Frontiers in Psychology, 7, Article 475. 10.3389/fpsyg.2016.00475 [PubMed: 27065934]

Licari MK, Alvares GA, Varcin K, Evans KL, Cleary D, Reid SL, Glasson EJ, Bebbington K, Reynolds JE, Wray J, & Whitehouse AJO (2020). Prevalence of motor difficulties in autism spectrum disorder: Analysis of a population-based cohort. Autism Research, 13(2), 298–306. 10.1002/aur.2230 [PubMed: 31625694]

*. Lim YH, Lee HC, Falkmer T, Allison GT, Tan T, Lee WL, & Morris SL (2019). Effect of visual information on postural control in adults with autism spectrum disorder. Journal of Autism and Developmental Disorders, 49(12), 4731–4739. 10.1007/s10803-018-3634-6 [PubMed: 29882108]

Lim YH, Licari M, Spittle AJ, Watkins RE, Zwicker JG, Downs J, & Finlay-Jones A (2021). Early motor function of children with autism spectrum disorder: A systematic review. Pediatrics, 147(2), Article e2020011270. 10.1542/peds.2020-011270 [PubMed: 33510035]

Lim YH, Partridge K, Girdler S, & Morris SL (2017). Standing postural control in individuals with autism spectrum disorder: Systematic review and meta-analysis. Journal of Autism and Developmental Disorders, 47(7), 2238–2253. 10.1007/s10803-017-3144-y [PubMed: 28508177]

*. Lindor E, Rinehart N, & Fielding J (2019). Distractor inhibition in autism spectrum disorder: Evidence of a selective impairment for individuals with co-occurring motor difficulties. Journal of Autism and Developmental Disorders, 49(2), 669–682. 10.1007/s10803-018-3744-1 [PubMed: 30203309]

*. Linke AC, Kinnear MK, Kohli JS, Fong CH, Lincoln AJ, Carper RA, & Müller R-A (2020). Impaired motor skills and atypical functional connectivity of the sensorimotor system in 40- to 65-year-old adults with autism spectrum disorders. Neurobiology of Aging, 85, 104–112. 10.1016/j.neurobiolaging.2019.09.018 [PubMed: 31732217]

Lipsey MW, & Wilson DB (2001). Practical meta-analysis. Sage Publications.

*. Liu T (2012). Motor milestone development in young children with autism spectrum disorders: An exploratory study. Educational Psychology in Practice, 28(3), 315–326. 10.1080/02667363.2012.684340

*. Liu T (2013). Sensory processing and motor skill performance in elementary school children with autism spectrum disorder. Perceptual and Motor Skills, 116(1), 197–209. 10.2466/10.25.PMS.116.1.197-209 [PubMed: 23829146]

*. Liu T, & Breslin CM (2013). Fine and gross motor performance of the MABC-2 by children with autism spectrum disorder and typically developing children. Research in Autism Spectrum Disorders, 7(10), 1244–1249. 10.1016/j.rasd.2013.07.002

*. Lopata C, Volker MA, Hamm EM, Sowinski JE, & Thomeer ML (2007). Motor and Visuomotor skills of children with Asperger's disorder: Preliminary findings. Perceptual and Motor Skills, 104(Suppl. 3), 1183–1192. 10.2466/pms.104.4.1183-1192 [PubMed: 17879650]

Lüdecke D (2018). esc: Effect size computation for meta analysis [R Package Version 0.5.1]. https://cran.r-project.org/web/packages/esc

Luhmann M, & Eid M (2012). Methodology of learning research: Meta-analyses. In Encyclopedia of the sciences of learning (pp. 2260–2263). Springer. 10.1007/978-1-4419-1428-6_1582

MacDonald M, Lord C, & Ulrich DA (2013). The relationship of motor skills and social communicative skills in school-aged children with autism spectrum disorder. Adapted Physical Activity Quarterly, 30, 271–282. 10.1123/apaq.30.3.271 [PubMed: 23860508]

*. Mache MA, & Todd TA (2016). Gross motor skills are related to postural stability and age in children with autism spectrum disorder. Research in Autism Spectrum Disorders, 23, 179–187. 10.1016/j.rasd.2016.01.001

Maenner MJ, Shaw KA, Baio J, Washington A, Patrick M, DiRienzo M, Christensen DL, Wiggins LD, Pettygrove S, Andrews JG, Lopez M, Hudson A, Baroud T, Schwenk Y, White T, Rosenberg CR, Lee LC, Harrington RA, Huston M, … Dietz PM (2020). Prevalence of autism spectrum disorder among children aged 8 years—Autism and developmental disabilities monitoring network, 11 sites, United States, 2016. Morbidity and Mortality Weekly Report: Surveillance Summaries, 69(4), 1–12. 10.15585/mmwr.ss6706a1

*. Manicolo O, Brotzmann M, Hagmann-von Arx P, Grob A, & Weber P (2019). Gait in children with infantile/atypical autism: Age-dependent decrease in gait variability and associations with motor skills. European Journal of Paediatric Neurology, 23(1), 117–125. 10.1016/j.ejpn.2018.09.011 [PubMed: 30482681]

*. Mattard-Labrecque C, Ben Amor L , & Couture MM (2013). Children with autism and attention difficulties: A pilot study of the association between sensory, motor, and adaptive behaviors. Journal of the Canadian Academy of Child and Adolescent Psychiatry [Journal de l'Académie Canadienne de Psychiatrie de l'enfant et de l'adolescent], 22(2), 139–146. [PubMed: 23667360]

McNaughton KA, & Redcay E (2020). Interpersonal synchrony in autism. Current Psychiatry Reports, 22(3), Article 12. 10.1007/s11920-020-1135-8 [PubMed: 32025922]

*. McPhillips M, Finlay J, Bejerot S, & Hanley M (2014). Motor deficits in children with autism spectrum disorder: A cross-syndrome study. Autism Research, 7(6), 664–676. 10.1002/aur.1408 [PubMed: 25258309]

*. Memari AH, Ghanouni P, Gharibzadeh S, Eghlidi J, Ziaee V, & Moshayedi P (2013). Postural sway patterns in children with autism spectrum disorder compared with typically developing children. Research in Autism Spectrum Disorders, 7(2), 325–332. 10.1016/j.rasd.2012.09.010

*. Milne E, White S, Campbell R, Swettenham J, Hansen P, & Ramus F (2006). Motion and form coherence detection in autistic spectrum disorder: Relationship to motor control and 2:4 digit ratio. Journal of Autism and Developmental Disorders, 36(2), 225–237. 10.1007/s10803-005-0052-3 [PubMed: 16477516]

*. Minshew NJ, Sung K, Jones BL, & Furman JM (2004). Underdevelopment of the postural control system in autism. Neurology, 63(11), 2056–2061. 10.1212/01.WNL.0000145771.98657.62 [PubMed: 15596750]

Moody EJ, & McIntosh DN (2006). Mimicry and autism: Bases and consequences of rapid, automatic matching behavior. In Imitation and the social mind: Autism and typical development (pp. 71–95). Guilford Press.

*. Morris SL, Foster CJ, Parsons R, Falkmer M, Falkmer T, & Rosalie SM (2015). Differences in the use of vision and proprioception for postural control in autism spectrum disorder. Neuroscience, 307, 273–280. 10.1016/j.neuroscience.2015.08.040 [PubMed: 26314635]

*. Morrison S, Armitano CN, Raffaele CT, Deutsch SI, Neumann SA, Caracci H, & Urbano MR (2018). Neuromotor and cognitive responses of adults with autism spectrum disorder compared to neurotypical adults. Experimental Brain Research, 236(8), 2321–2332. 10.1007/s00221-018-5300-9 [PubMed: 29876630]

Moruzzi S, Ogliari A, Ronald A, Happé F, & Battaglia M (2011). The nature of covariation between autistic traits and clumsiness: A twin study in a general population sample. Journal of Autism and Developmental Disorders, 41(12), 1665–1674. 10.1007/s10803-011-1199-8 [PubMed: 21347613]

Mosconi MW, & Sweeney JA (2015). Sensorimotor dysfunctions as primary features of autism spectrum disorders. Science China. Life Sciences, 58(10), 1016–1023. 10.1007/s11427-015-4894-4 [PubMed: 26335740]

*. Nobile M, Perego P, Piccinini L, Mani E, Rossi A, Bellina M, & Molteni M (2011). Further evidence of complex motor dysfunction in drug naive children with autism using automatic motion analysis of gait. Autism: An International Journal of Research and Practise, 15(3), 263–283. 10.1177/1362361309356929

Noel JP, De Niear MA, Lazzara NS, & Wallace MT (2017). Uncoupling between multisensory temporal function and nonverbal turn-taking in autism spectrum disorder. IEEE Transactions on Cognitive and Developmental Systems, 10(4), 973–982. 10.1109/TCDS.2017.2778141

*. Noterdaeme M, Mildenberger K, Minow F, & Amorosa H (2002). Evaluation of neuromotor deficits in children with autism and children with a specific speech and language disorder. European Child and Adolescent Psychiatry, 11(5), 219–225. 10.1007/s00787-002-0285-z [PubMed: 12469239]

†. Ornitz EM, Guthrie D, & Farley AH (1977). The early development of autistic children. Journal of Autism and Childhood Schizophrenia, 7(3), 207–229. 10.1007/BF01538999 [PubMed: 71292]

Ouzzani M, Hammady H, Fedorowicz Z, & Elmagarmid A (2016). Rayyan-a web and mobile app for systematic reviews. Systematic Reviews, 5(1), Article 210. 10.1186/s13643-016-0384-4 [PubMed: 27919275]

*†. Ozonoff S, Young GS, Goldring S, Greiss-Hess L, Herrera AM, Steele J, Macari S, Hepburn S, & Rogers SJ (2008). Gross motor development, movement abnormalities, and early identification of autism. Journal of Autism and Developmental Disorders, 38(4), 644–656. 10.1007/s10803-007-0430-0 [PubMed: 17805956]

*. Pan CY (2014). Motor proficiency and physical fitness in adolescent males with and without autism spectrum disorders. Autism: An International Journal of Research and Practise, 18(2), 156–165. 10.1177/1362361312458597

*. Pan C-Y, Tsai C-L, & Chu C-H (2009). Fundamental movement skills in children diagnosed with autism spectrum disorders and attention deficit hyperactivity disorder. Journal of Autism and Developmental Disorders, 39(12), 1694–1705. 10.1007/s10803-009-0813-5 [PubMed: 19588236]

*. Papadopoulos N, McGinley J, Tonge B, Bradshaw J, Saunders K, Murphy A, & Rinehart N (2012). Motor proficiency and emotional/behavioural disturbance in autism and Asperger's disorder: Another piece of the neurological puzzle? Autism: An International Journal of Research and Practise, 16(6), 627–640. 10.1177/1362361311418692

Pierce K, Gazestani VH, Bacon E, Barnes CC, Cha D, Nalabolu S, Lopez L, Moore A, Pence-Stophaeros S, & Courchesne E (2019). Evaluation of the diagnostic stability of the early autism spectrum disorder phenotype in the general population starting at 12 months. JAMA Pediatrics, 173(6), 578–587. 10.1001/jamapediatrics.2019.0624 [PubMed: 31034004]

Plomin R, & Deary IJ (2015). Genetics and intelligence differences: Five special findings. Molecular Psychiatry, 20(1), 98–108. 10.1038/mp.2014.105 [PubMed: 25224258]

*. Price KJ, Edgell D, & Kerns KA (2012). Timing deficits are implicated in motor dysfunction in Asperger's syndrome. Research in Autism Spectrum Disorders, 6(2), 857–860. 10.1016/j.rasd.2011.11.007

*. 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. 10.1007/s10803-006-0170-6 [PubMed: 16868847]

*. Pusponegoro HD, Efar P, Soedjatmiko, Soebadi A, Firmansyah A, Chen HJ, & Hung KL (2016). Gross motor profile and its association with socialization skills in children with autism spectrum disorders. Pediatrics and Neonatology, 57(6), 501–507. 10.1016/j.pedneo.2016.02.004 [PubMed: 27161079]

Pustejovsky JE (2015). clubSandwich: Cluster-robust (sandwich) variance estimators with small-sample corrections [R package version 0.4.1]. https://cran.r-project.org/web/packages/clubSandwich

*. Radonovich KJ, Fournier KA, & Hass CJ (2013). Relationship between postural control and restricted, repetitive behaviors in autism spectrum disorders. Frontiers in Integrative Neuroscience, 7, Article 28. 10.3389/fnint.2013.00028 [PubMed: 23675326]

Rinehart N, & McGinley J (2010). Is motor dysfunction core to autism spectrum disorder? Developmental Medicine and Child Neurology, 52(8), 697–697. 10.1111/j.1469-8749.2010.03631.x [PubMed: 20345958]

*. Rinehart NJ, Tonge BJ, Bradshaw JL, Iansek R, Enticott PG, & McGinley J (2006). Gait function in high-functioning autism and Asperger's disorder : Evidence for basal-ganglia and cerebellar involvement? European Child and Adolescent Psychiatry, 15(5), 256–264. 10.1007/s00787-006-0530-y [PubMed: 16554961]

*. Rinehart NJ, Tonge BJ, Iansek R, McGinley J, Brereton AV, Enticott PG, & Bradshaw JL (2006). Gait function in newly diagnosed children with autism: Cerebellar and basal ganglia related motor disorder. Developmental Medicine and Child Neurology, 48(10), 819–824. 10.1017/S0012162206001769 [PubMed: 16978461]

Rodgers MA, & Pustejovsky JE (2021). Evaluating meta-analytic methods to detect selective reporting in the presence of dependent effect sizes. Psychological Methods, 26(2), 141–160. 10.1037/met0000300

*. Rogers SJ, Hepburn S, & Wehner E (2003). Parent reports of sensory symptoms in toddlers with autism and those with other developmental disorders. Journal of Autism and Developmental Disorders, 33(6), 631–642. 10.1023/B:JADD.0000006000.38991.a7 [PubMed: 14714932]

Rohatgi A (2019). WebPlotDigitizer. https://automeris.io/WebPlotDigitizer

Rosenbaum DA (2005). The Cinderella of psychology: The neglect of motor control in the science of mental life and behavior. American Psychologist, 60(4), 308–317. 10.1037/0003-066X.60.4.308 [PubMed: 15943523]

Rosner B (1983). Percentage points for a generalized ESD many-outlier procedure. Technometrics, 25(2), 165–172. 10.1080/00401706.1983.10487848

Sacrey L-AR, Germani T, Bryson SE, & Zwaigenbaum L (2014). Reaching and grasping in autism spectrum disorder: A review of recent literature. Frontiers in Neurology, 5, Article 6. 10.3389/fneur.2014.00006 [PubMed: 24478753]

*†. Sacrey L-AR, Zwaigenbaum L, Bryson S, Brian J, & Smith IM (2018). The reach-to-grasp movement in infants later diagnosed with autism spectrum disorder: A high-risk sibling cohort study. Journal of Neurodevelopmental Disorders, 10(1), Article 41. 10.1186/s11689-018-9259-4 [PubMed: 30587102]

*. Sahlander C, Mattsson M, & Bejerot S (2008). Motor function in adults with Asperger's disorder: A comparative study. Physiotherapy Theory and Practice, 24(2), 73–81. 10.1080/15368370701380843 [PubMed: 18432510]

*. Schurink J, Hartman E, Scherder EJA, Houwen S, & Visscher C (2012). Relationship between motor and executive functioning in school-age children with pervasive developmental disorder not otherwise specified. Research in Autism Spectrum Disorders, 6(2), 726–732. 10.1016/j.rasd.2011.10.013

*. Siaperas P, Ring HA, McAllister CJ, Henderson S, Barnett A, Watson P, & Holland AJ (2012). Atypical movement performance and sensory integration in Asperger's syndrome. Journal of Autism and Developmental Disorders, 42(5), 718–725. 10.1007/s10803-011-1301-2 [PubMed: 21643861]

*. Somogyi E, Kapitány E, Kenyeres K, Donauer N, Fagard J, & Kónya A (2016). Visual feedback increases postural stability in children with autism spectrum disorder. Research in Autism Spectrum Disorders, 29–30, 48–56. 10.1016/j.rasd.2016.06.001

*. Soorya LV (2003). Evaluation of motor proficiency and apraxia in autism: Effects on sign language acquisition [Doctoral Dissertation]. Binghamton University.

*. Staples KL (2009). Fundamental movement skills and motor planning abilities among children with autism spectrum disorders [Doctoral Dissertation]. McGill University.

*. Stoit AMB, van Schie HT, Slaats-Willemse DIE, & 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. 10.1007/s10803-013-1825-8 [PubMed: 23619948]

*. Stone WL, Ousley OY, & Littleford CD (1997). Motor imitation in young children with autism: What's the object? Journal of Abnormal Child Psychology, 25(6), 475–485. 10.1023/A:1022685731726 [PubMed: 9468108]

*. Sumner E, Leonard HC, & Hill EL (2016). Overlapping phenotypes in autism spectrum disorder and developmental coordination disorder: A cross-syndrome comparison of motor and social skills.

Journal of Autism and Developmental Disorders, 46(8), 2609–2620. 10.1007/s10803-016-2794-5 [PubMed: 27126816]

Tanner-Smith EE, Tipton E, & Polanin JR (2016). Handling Complex meta-analytic data structures using robust variance estimates: A tutorial in R. Journal of Developmental and Life-Course Criminology, 2(1), 85–112. 10.1007/s40865-016-0026-5

Tipton E (2015). Small sample adjustments for robust variance estimation with meta-regression. Psychological Methods, 20(3), 375–393. 10.1037/met0000011 [PubMed: 24773356]

*. Tomchek SD, Little LM, & Dunn W (2015). Sensory pattern contributions to developmental performance in children with autism spectrum disorder. The American Journal of Occupational Therapy, 69(5), 6905185040p1–6905185040p10. 10.5014/ajot.2015.018044

*†. Travers BG, Mason AH, Gruben KG, Dean DC, & McLaughlin K (2018). Standing balance on unsteady surfaces in children on the autism spectrum: The effects of IQ. Research in Autism Spectrum Disorders, 51(July 2017), 9–17. 10.1016/j.rasd.2018.03.008 [PubMed: 30333859]

*†. Travers BG, Powell PS, Klinger LG, & Klinger MR (2013). Motor difficulties in autism spectrum disorder: Linking symptom severity and postural stability. Journal of Autism and Developmental Disorders, 43(7), 1568–1583. 10.1007/s10803-012-1702-x [PubMed: 23132272]

Van Overwalle F (2009). Social cognition and the brain: A meta-analysis. Human Brain Mapping, 30(3), 829–858. 10.1002/hbm.20547 [PubMed: 18381770]

Van Overwalle F, Baetens K, Mariën P, & Vandekerckhove M (2014). Social cognition and the cerebellum: A meta-analysis of over 350 fMRI studies. NeuroImage, 86, 554–572. 10.1016/j.neuroimage.2013.09.033 [PubMed: 24076206]

*. Vanvuchelen M, Van Schuerbeeck L, & Braeken MAKA (2017). Screening accuracy of the parent-completed Ages and Stages Questionnaires—second edition as a broadband screener for motor problems in preschoolers with autism spectrum disorders. Autism: An International Journal of Research and Practise, 21(1), 29–36. 10.1177/1362361315621703

Viechtbauer W (2010). Conducting meta-analyses in R with the metafor package. Journal of Statistical Software, 36(3), 1–48. 10.18637/jss.v036.i03

*. Vilensky JA, Damasio AR, & Maurer RG (1981). Gait disturbances in patients with autistic behavior: A preliminary study. Archives of Neurology, 38(10), 646–649. 10.1001/archneur.1981.00510100074013 [PubMed: 7295109]

Wang MV, Lekhal R, Aarø LE, & Schjølberg S (2014). Co-development of early communication and motor skills. Child: Care, Health and Development, 40, 77–84. 10.1111/cch.12003 [PubMed: 22970997]

*†. Wang Z, Hallac RR, Conroy KC, White SP, Kane AA, Collinsworth AL, Sweeney JA, & Mosconi MW (2016). Postural orientation and equilibrium processes associated with increased postural sway in autism spectrum disorder (ASD). Journal of Neurodevelopmental Disorders, 8, Article 17. 10.1186/s11689-016-9178-1 [PubMed: 27186239]

*. Weimer AK, Schatz AM, Lincoln A, Ballantyne AO, & Trauner DA (2001). “Motor” impairment in Asperger syndrome: Evidence for a deficit in proprioception. Journal of Developmental and Behavioral Pediatrics, 22(2), 92–101. 10.1097/00004703-200104000-00002 [PubMed: 11332785]

West KL (2019). Infant motor development in autism spectrum disorder: A synthesis and meta-analysis. Child Development, 90(6), 2053–2070. 10.1111/cdev.13086 [PubMed: 29766496]

*. West KL, Leezenbaum NB, Northrup JB, & Iverson JM (2019). The relation between walking and language in infant siblings of children with autism spectrum disorder. Child Development, 90(3), e356–e372. 10.1111/cdev.12980 [PubMed: 29058782]

WHO Multicentre Growth Reference Study Group. (2006). WHO motor development study: Windows of achievement for six gross motor development milestones. Acta Paediatrica Supplement, 450, 86–95. 10.1111/j.1651-2227.2006.tb02379.x [PubMed: 16817682]

Whyatt C, & Craig C (2013a). Sensory-motor problems in Autism. Frontiers in Integrative Neuroscience, 7, Article 51. 10.3389/fnint.2013.00051 [PubMed: 23882194]

Whyatt C, & Craig CM (2013b). Interceptive skills in children aged 9–11 years, diagnosed with autism spectrum disorder. Research in Autism Spectrum Disorders, 7(5), 613–623. 10.1016/j.rasd.2013.01.003

*. Whyatt CP, & Craig CM (2012). Motor skills in children aged 7–10 years, diagnosed with autism spectrum disorder. Journal of Autism and Developmental Disorders, 42(9), 1799–1809. 10.1007/s10803-011-1421-8 [PubMed: 22180003]

*. Wild KS, Poliakoff E, Jerrison A, & Gowen E (2012). Goal-directed and goal-less imitation in autism spectrum disorder. Journal of Autism and Developmental Disorders, 42(8), 1739–1749. 10.1007/s10803-011-1417-4 [PubMed: 22146933]

*. Wisdom SN, Dyck MJ, Piek JP, Hay D, & Hallmayer J (2007). Can autism, language and coordination disorders be differentiated based on ability profiles? European Child & Adolescent Psychiatry, 16(3), 178–186. 10.1007/s00787-006-0586-8 [PubMed: 17136301]

World Health Organization. (2016). International statistical classification of diseases and related health problems (10th ed.). https://icd.who.int/browse10/2016/en

*. Yang H-C, Lee I-C, & Lee I-C (2014). Visual feedback and target size effects on reach-to-grasp tasks in children with autism. Journal of Autism and Developmental Disorders, 44(12), 3129–3139. 10.1007/s10803-014-2165-z [PubMed: 24974254]

*. Zachor DA, Ilanit T, & Ben Itzchak E (2010). Autism severity and motor abilities correlates of imitation situations in children with autism spectrum disorders. Research in Autism Spectrum Disorders, 4(3), 438–443. 10.1016/j.rasd.2009.10.016

Zampella CJ, Bennetto L, & Herrington JD (2020). Computer vision analysis of reduced interpersonal affect coordination in youth with autism spectrum disorder. Autism Research, 13(12), 2133–2142. 10.1002/aur.2334 [PubMed: 32666690]

Zampella CJ, Wang LAL, Haley M, Hutchinson AG, & de Marchena A (2021). Motor skill differences in autism spectrum disorder: A clinically focused review. Current Psychiatry Reports, 23(10), Article 64. 10.1007/s11920-021-01280-6 [PubMed: 34387753]

Public Significance Statement

These meta-analyses reveal that individuals on the autism spectrum exhibit a large deficit in gross motor skills compared to neurotypical individuals, regardless of the individual's age, sex, or cognitive ability. Further, gross motor impairment is modestly associated with social impairment for autistic individuals.

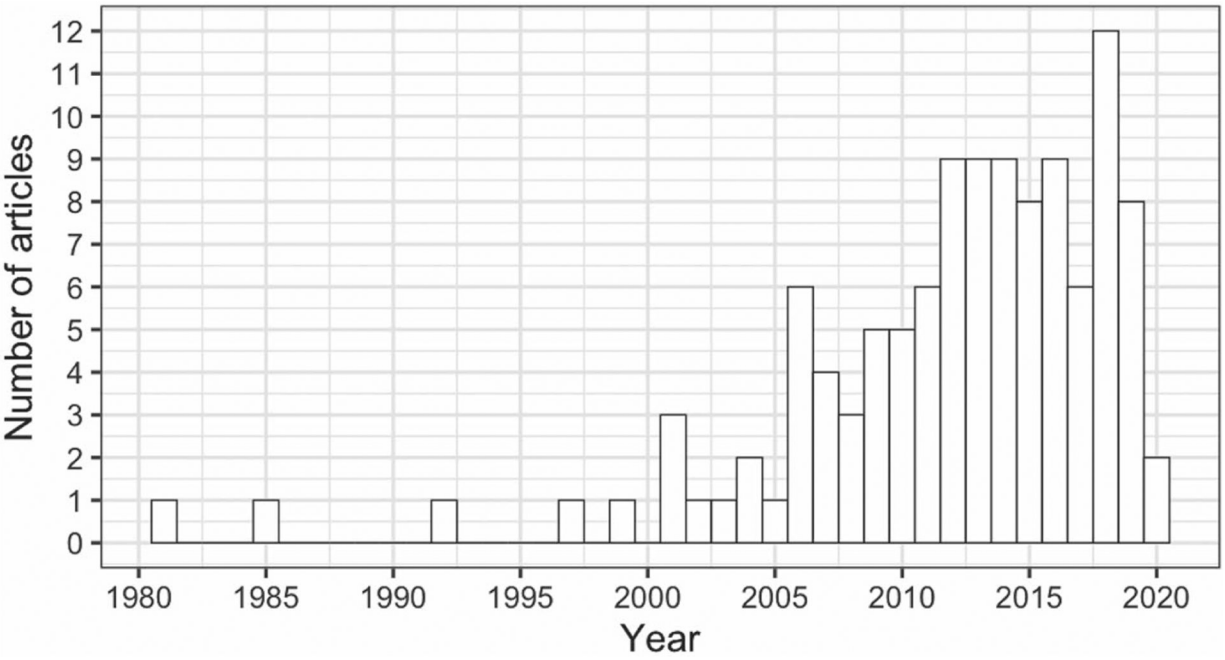

Figure 1.
Histogram of the Year of Publication of the Articles Included in This Meta-Analysis

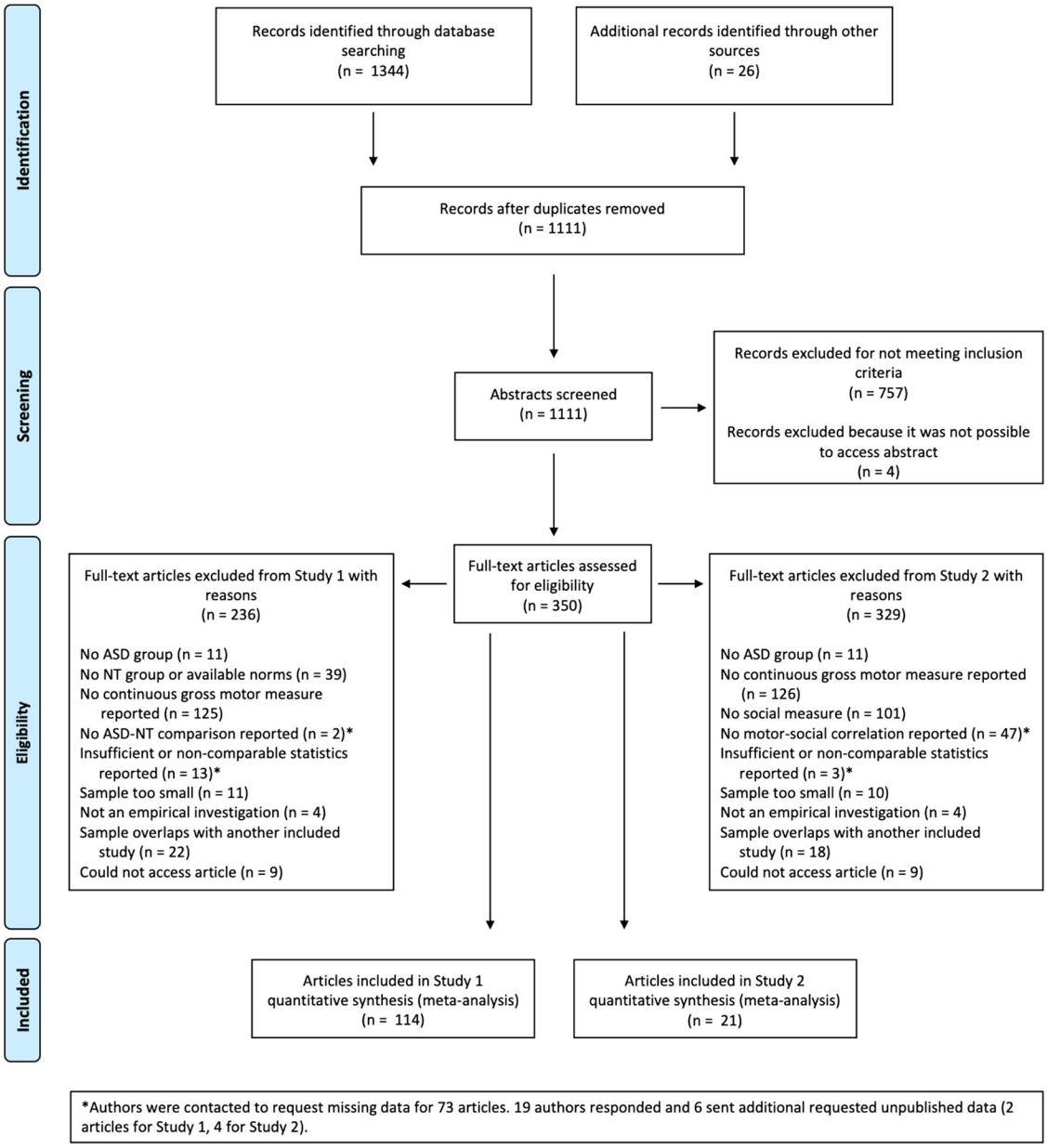

Figure 2.

Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Flowchart of the Search Process and Exclusion of Papers

Note. ASD = autism spectrum disorder; NT = neurotypical. See the online article for the color version of this figure.

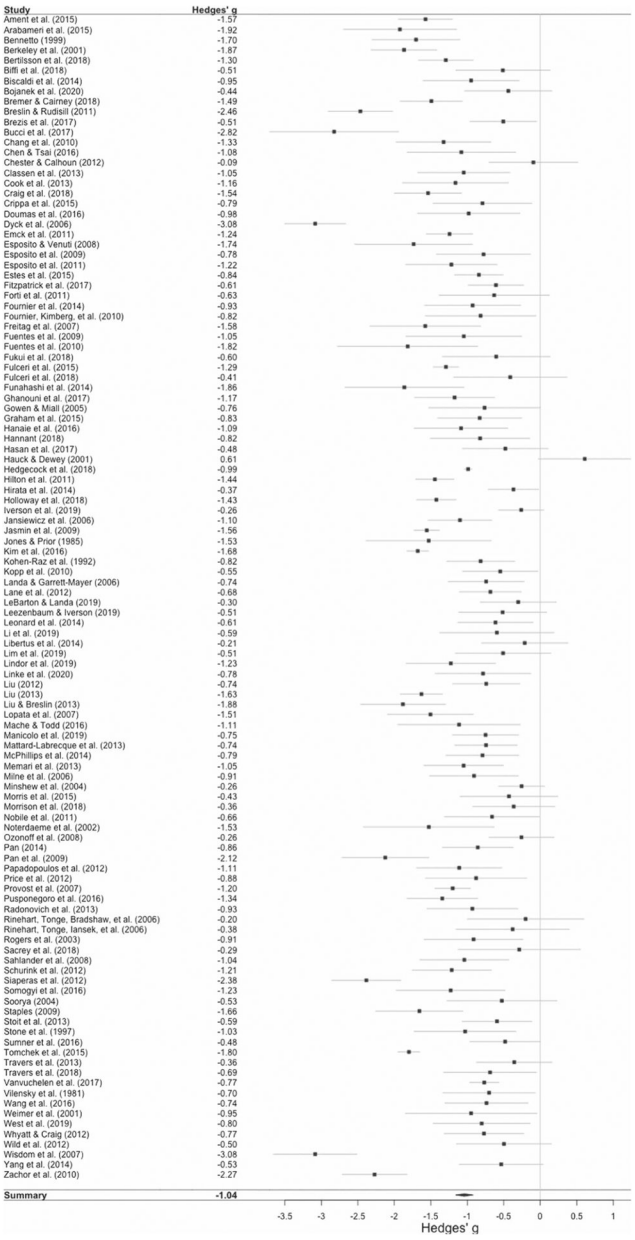

Figure 3.
Forest Plot of Study-Level Aggregated Mean Difference Effects Included in Study 1

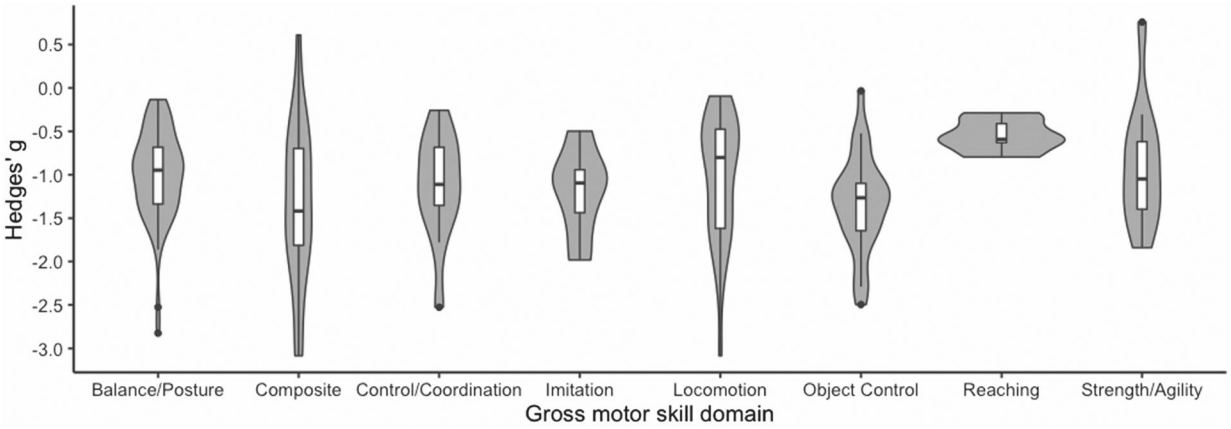

Figure 4.

Plot of the Distribution of Group Difference Effect Sizes for Each Gross Motor Skill Domain

Note. Aggregate effect sizes at the study level were used to produce this plot. Violin plots represent the smoothed distribution density of effects in each category.

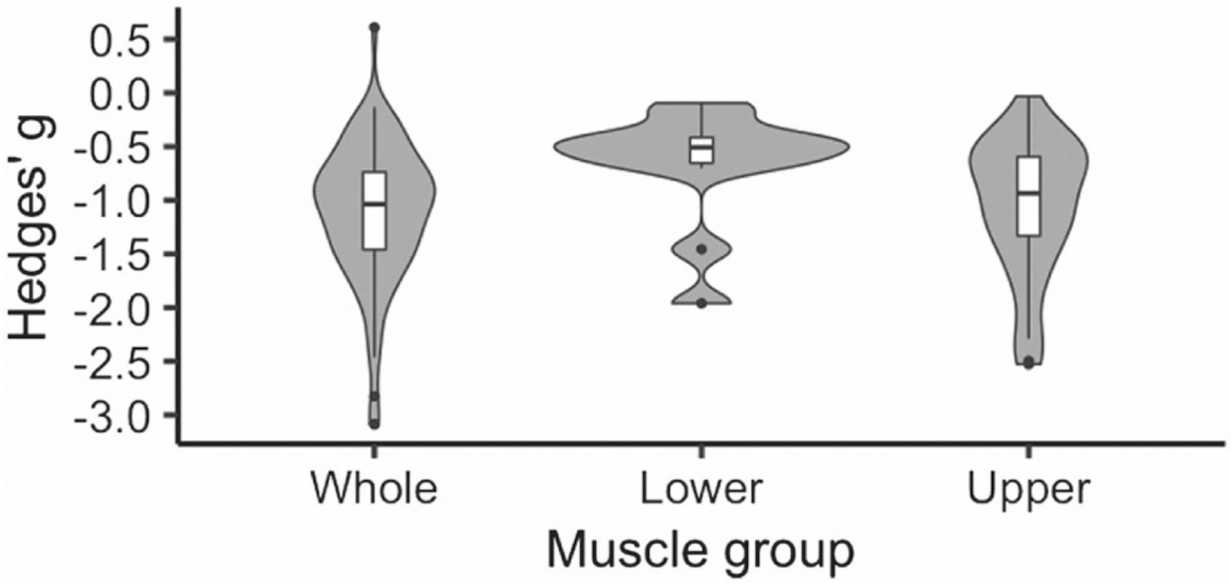

Figure 5.

Plot of the Distribution of Group Difference Effect Sizes for Each Gross Motor Muscle Group

Note. Aggregate effect sizes at the study level were used to produce this plot. Violin plots represent the smoothed distribution density of effects in each category. “Whole” represents gross motor behaviors that recruit muscle groups across the whole body (e.g., balancing, jumping jacks); “lower” represents gross motor behaviors that recruit the lower extremities (e.g., kicking a ball); “upper” represents gross motor behaviors that recruit the upper extremities (e.g., reaching toward an object).

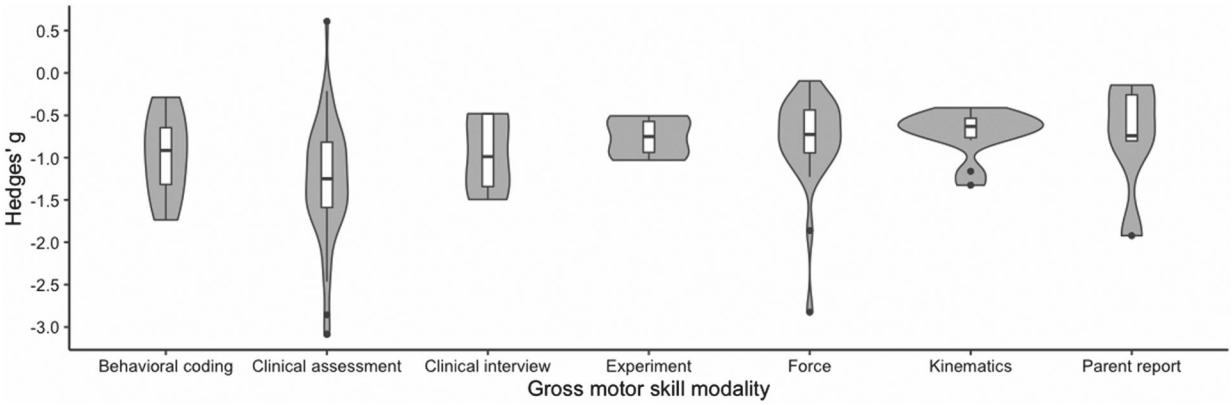

Figure 6.

Plot of the Distribution of Group Difference Effect Sizes for Each Gross Motor Measurement Modality</p>*Note.* Aggregate effect sizes at the study level were used to produce this plot. Violin plots represent the smoothed distribution density of effects in each category.

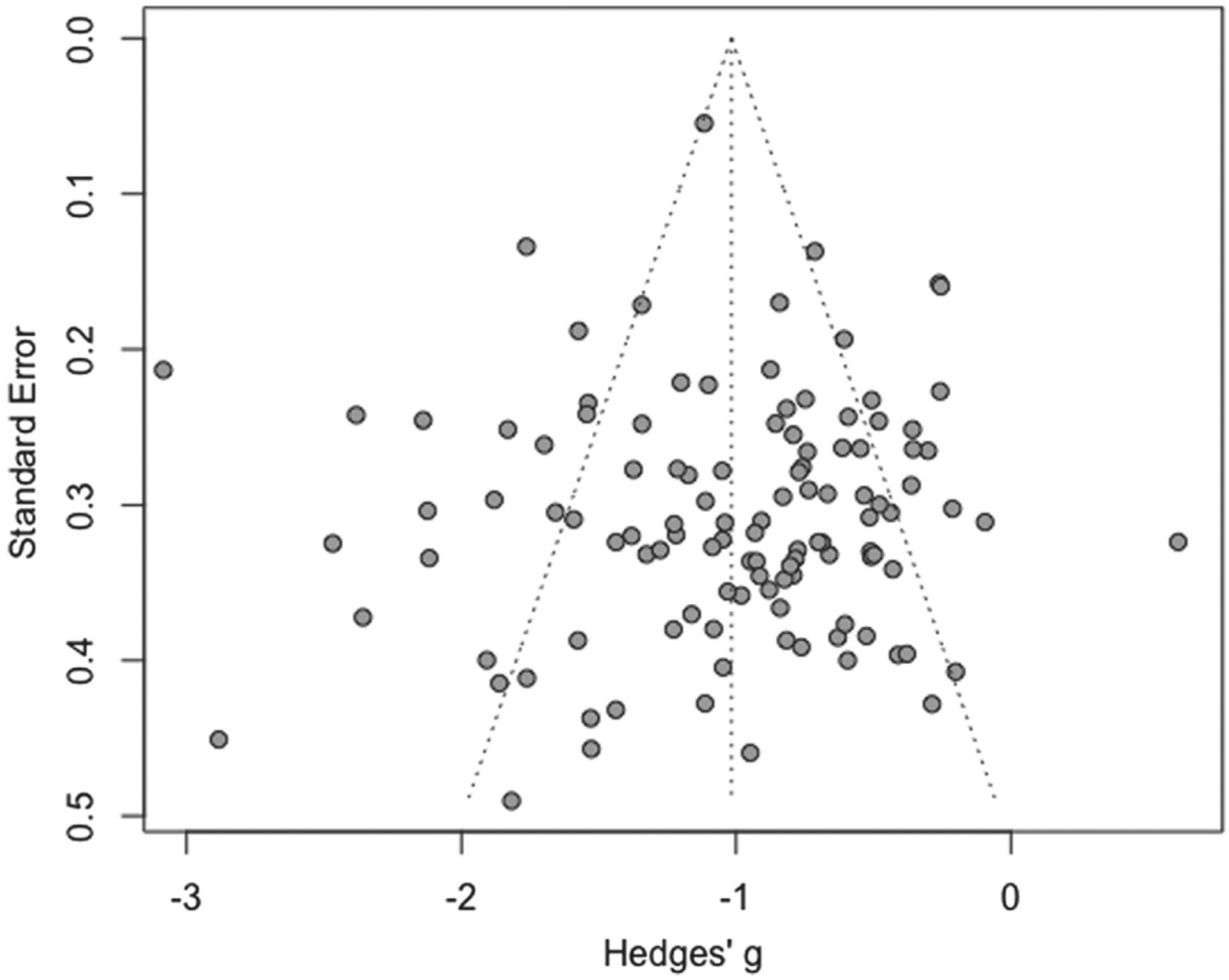

Figure 7.
Funnel Plot of All Aggregate Study-Level Group Difference Effect Sizes by Standard Error for Articles Included in Study 1

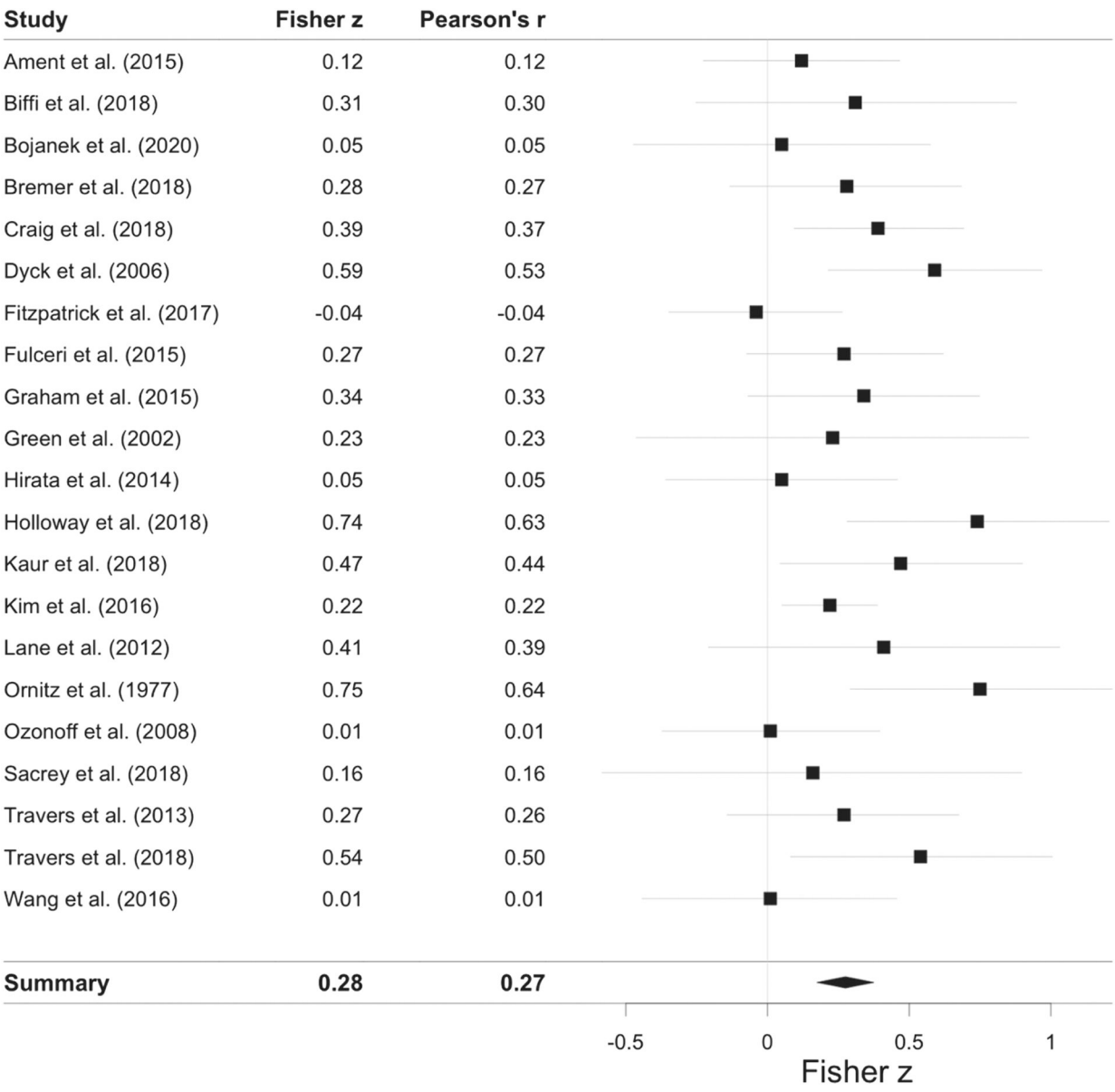

Figure 8.
Forest Plot of Study-Level Aggregated Correlation Coefficients Included in Study 2

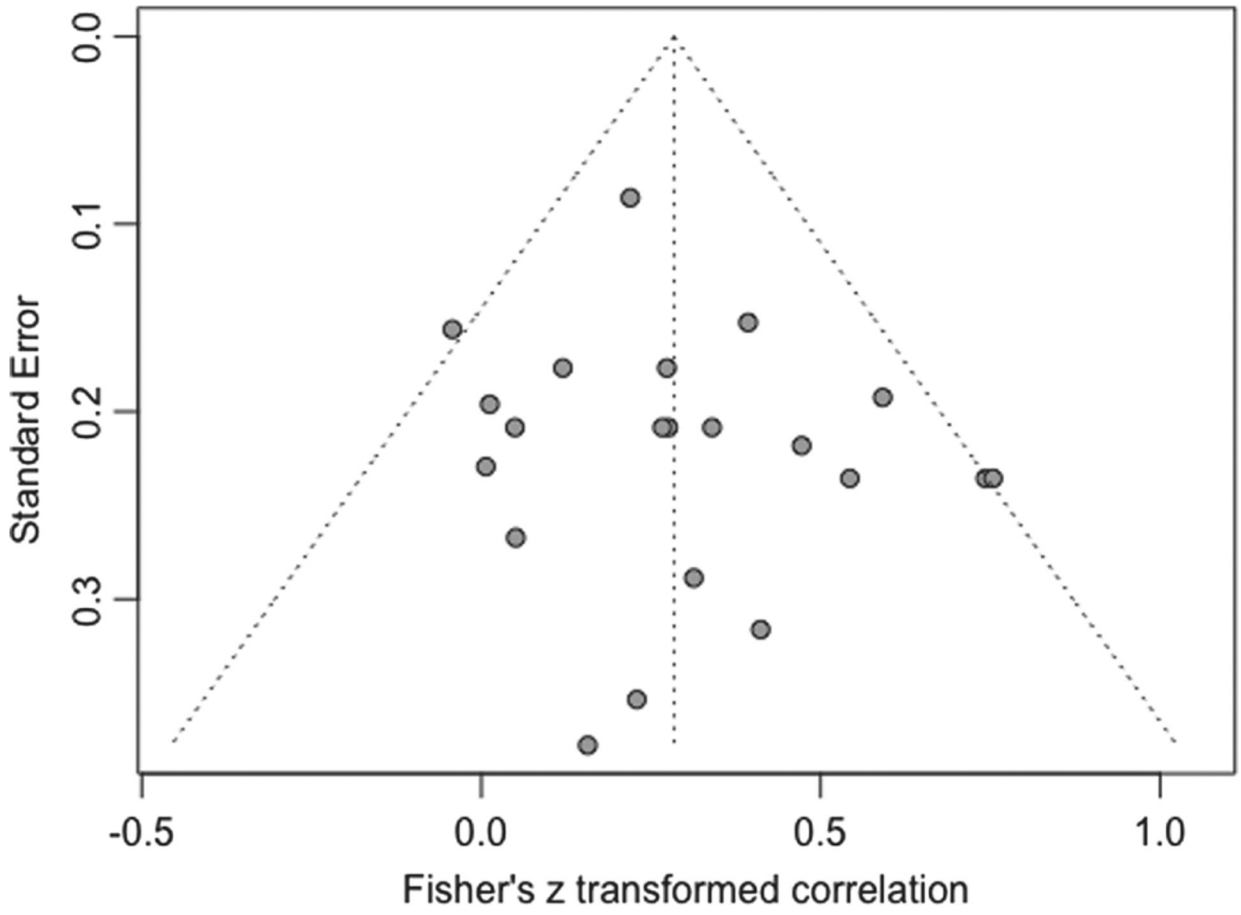

Figure 9.
Funnel Plot of All Aggregate Study-Level Fisher's Z-Transformed Correlation Effect Sizes by Standard Error for Articles Included in Study 2

Table 1

Descriptions and Examples of Coded Gross Motor Skill Domains

Gross motor skill domain	Description	Examples
Broad composite	An overall gross motor composite from a standardized measure or the combination of two or more of the other domains.	Peabody Developmental Motor Scale Gross Motor Quotient; Vineland Gross Motor v-Scale Score
Locomotion	A measure of some aspect of movement used to transport one's body from one place to another.	Kinemetric analysis of gait; age child first began to crawl
Balance and posture	A measure of the ability to maintain particular body postures by controlling the body within its center of gravity.	Postural sway; one-legged balance time
Imitation	A measure of the quality of imitation of complex gross motor movements.	Imitation of full-body postures; imitation of sinusoidal arm movements
Object control	A measure of some aspect of the ability to control or manipulate objects.	Catching accuracy; kicking accuracy
Reaching	A measure of some aspect of goal-directed reaching (i.e., the reach-to-grasp movement) from a seated position.	Movement time of reach toward object; age child first began reaching unilaterally
Motor control and coordination	A measure of the ability to regulate, control, plan, or coordinate gross motor movement.	Coordination between left and right limbs; movement variability during experimental task
Strength and agility	A measure of muscle strength, muscle tone, movement speed, or agility.	Ability to change directions quickly while running; how quickly a participant can move a handle along a track

Table 2

Items Assessed to Determine Methodological Quality Ratings

Question	Study 1 or 2?	Answer choices and coded values	Mean value across articles in Study 1	Mean value across articles in Study 2
Was the article peer reviewed?	Studies 1 and 2	Yes = 1, No = 0	0.97	1.00
Were the research questions/objectives of the study clearly stated?	Studies 1 and 2	Yes = 1, No = 0	0.99	1.00
Was a power analysis or other sample size justification provided?	Studies 1 and 2	Yes = 1, No = 0	0.07	0.05
Was the recruitment method for the ASD group reported?	Studies 1 and 2	Yes = 1, No = 0	0.88	1.00
Was the recruitment method for the NT group reported?	Study 1 only	Yes = 1, No = 0, Normative NT group = 1	0.86	Not applicable
Did the autistic participants have comorbid medical or psychiatric diagnoses?	Studies 1 and 2	Yes = 0, No = 1, Unclear = 0	0.21	0.24
Does the sampling method or sample composition have potential to bias generalizability of results?	Studies 1 and 2	Yes = 0, No = 1	0.71	0.76
Did the investigators confirm ASD diagnosis in the autistic sample?	Studies 1 and 2	Yes = 1, No = 0	0.77	0.86
Did the investigators use a gold-standard diagnostic tool (ADOS and/or ADI) to confirm ASD diagnosis?	Studies 1 and 2	Yes = 1, No = 0	0.58	0.71
Were the investigators blinded to participants' diagnostic status?	Study 1 only	Yes = 1, No = 0	0.12	Not applicable
Did the investigators match the ASD to the NT group on chronological age, sex, IQ, or developmental age?	Study 1 only	Yes = 1, No = 0, Normative NT group = 1, Not reported = 0	0.95	Not applicable
Does the gross motor measure rely solely on parent report?	Studies 1 and 2	Yes = 0, No = 1	0.96	0.95
Does the social measure rely solely on parent report?	Study 2 only	Yes = 0, No = 1	Not applicable	0.57
Is there evidence of selective reporting of results?	Studies 1 and 2	Yes = 0, No = 1	0.94	0.90
Is the funding source for the study reported?	Studies 1 and 2	Yes = 1, No = 0	0.70	0.81
Is there potential for author conflict (i.e., evidence that author or data collectors would benefit from reported findings)?	Studies 1 and 2	Yes = 0, No = 1	0.99	1.00

Note. ASD = autism spectrum disorder; ADOS = autism diagnostic observation schedule; ADI = Autism Diagnostic Interview; IQ = intelligence quotient (or other measure of cognitive ability); NT = neurotypical.

Table 3

Table of Results of Moderator Analyses for Study 1

Moderator	Hedges' *g*/β	95% CI	*N*	*M*	I^2	*F*/*t* (*df*)	*p*
Gross motor skill type			114	791	87.20	13.59 (7, 31.15)	<.001
Balance and posture	-0.95_{a}	[−1.09, −0.82]	64	311			
Composite	-1.3_{abc}	[−1.90, −0.69]	22	38			
Control and coordination	-1.09_{abc}	[−1.66, −0.53]	12	17			
Imitation	1.07_{abc}	[−1.63, −0.51]	6	17			
Locomotion	-0.90_{abc}	[−1.28, −0.52]	33	280			
Object control	-1.37_{b}	[−1.74, −1.00]	27	30			
Reaching	-0.54_{c}	[−0.87, −0.21]	9	83			
Strength and agility	1.07_{abc}	[−1.55, −0.59]	11	15			
Muscle group			114	791	87.30	50.84 (2, 31.05)	<.001
Whole body/combined	-1.11_{a}	[−1.25, −0.97]	96	443			
Lower	-0.52_{b}	[−0.90, −0.13]	12	208			
Upper	-0.94_{ac}	[−1.31, −0.58]	38	140			
Gross motor measurement modality			114	791	85.12	4.28 (12.90)	.014
Behavioral coding	-0.97_{ab}	[−1.41, −0.53]	7	66			
Clinical assessment	-1.27_{a}	[−2.19, −0.36]	60	136			
Clinical interview	-1.02_{ab}	[−2.08, 0.03]	5	13			
Experimental	0.75_{ab}	[−1.71, 0.21]	4	8			
Force and pressure	-0.77_{b}	[−1.67, 0.13]	28	333			
Kinematics	-0.70_{b}	[−1.57, 0.16]	13	176			
Parent Questionnaire	-0.74_{ab}	[−1.94, 0.45]	5	59			
ASD subgroup			114	791	87.31	4.43 (3.58)	.104
ASD	−1.00	[−1.12, −0.88]	82	466			
Asperger	−1.16	[−1.80, −0.52]	10	80			
Autism	−1.12	[−1.65, −0.59]	25	242			
PDD-NOS	−1.41	[−5.14, 2.33]	2	3			
Study quality	−0.01	[−0.07, 0.05]	114	791	87.65	−0.39 (32.56)	.701

Moderator	Hedges' *g*/β	95% CI	*N*	*M*	I^2	*F*/*t* (*df*)	*p*
Sex	0.00	[−0.01, 0.00]	101	693	85.20	−0.74 (9.19)	.477
Age	0.01	[0.00, 0.02]	105	681	86.94	1.39 (11.18)	.190
IQ	0.01	[−0.01, 0.02]	64	409	82.85	0.86 (13.74)	.403

Note. Within categorical moderators, subscripts that do not share letters represent significant pairwise comparison after Bonferroni correction for multiple comparisons. For noncontinuous variables, the beta coefficients correspond to Hedges' *g*. β = beta coefficient; 95% CI = 95% confidence interval; *N* = number of studies; *M* = number of effects; *df* = degrees of freedom; ASD = autism spectrum disorder; PDD-NOS = pervasive developmental disorder-not otherwise specified; IQ = intelligence quotient.

Table 4

Table of Results of Moderator Analyses for Study 2

Moderator	Fisher's *z*/β	95% CI	*N*	*M*	I^2	*F*/*t* (*df*)	*p*
Gross motor skill type			21	170	65.11	1.29 (4.13)	.411
Balance and posture	0.28	[0.11, 0.45]	14	68			
Composite	0.36	[−0.2, 0.91]	4	8			
Control and coordination	0.22	[−0.66, 1.10]	4	8			
Locomotion	0.20	[−0.26, 0.66]	5	59			
Object control	0.30	[−0.35, 0.94]	7	13			
Reaching	0.16	[−0.17, 0.49]	1	14			
Muscle group			20	126	62.35	−0.59 (6.35)	.576
Whole body/combined	0.30	[0.18, 0.42]	18	103			
Upper	−0.13	[−0.50, 0.24]	6	23			
Gross motor measurement modality			20	169	62.64	0.63 (2.20)	.608
Behavioral coding	0.04	[−1.68, 1.76]	2	21			
Clinical assessment	0.31	[−2.71, 3.32]	10	41			
Clinical interview	0.19	[−2.71, 3.09]	1	2			
Experimental	0.46	[−2.69, 3.62]	1	1			
Social skill type			21	170	61.84	0.28 (0.54)	.875
Adaptive	0.39	[−1.47, 2.25]	2	8			
Composite	0.38	[−2.32, 3.09]	5	20			
Social cognition	0.39	[−2.24, 3.01]	3	29			
Social communication	0.20	[−2.89, 3.29]	14	100			
Social motivation	0.08	[−3.22, 3.38]	2	13			
Social skill measurement modality			20	167	61.73	1.28 (10.54)	.318
Clinical assessment	0.20	[−0.04, 0.43]	8	30			
Clinical interview	0.18	[−0.34, 0.71]	8	63			
Experimental	0.37	[−0.14, 0.88]	1	3			
Parent/teacher report			8	74			
Measurement modality congruence			21	170	61.23	0.28 (3.94)	.790
Incongruent	0.27	[0.15, 0.38]	18	160			

Moderator	Fisher's *z*/β	95% CI	*N*	*M*	I^2	*F*/*t* (*df*)	*p*
Congruent	−0.16	[−0.52, 0.2]	5	10			
ASD subgroup			20	166	61.92	0.76 (2.75)	.508
ASD	0.25	[0.15, 0.35]	17	144			
Autism	−0.17	[−0.52, 0.18]	3	22			
Study quality	−0.04	[−0.11, 0.04]	21	170	61.02	−1.16 (7.81)	.282
Sex	0.00	[−0.01, 0.02]	17	148	65.01	0.48 (3.77)	.661
Age	−0.01	[−0.03, 0.02]	19	166	61.99	−0.80 (4.14)	.470
IQ	−0.01	[−0.02, 0]	16	139	62.66	−1.95 (2.32)	.173

Note. For noncontinuous variables, the beta coefficients correspond to Fisher's *z*. β = beta coefficient; 95% CI = 95% confidence interval; *N* = number of studies; *M* = number of effects; *df* = degrees of freedom; ASD = autism spectrum disorder; IQ = intelligence quotient.