Author Manuscript

Author Manuscript

Author Manuscript

Author Manuscript

HHS Public Access

Author manuscript

Curr Opin Neurol. Author manuscript; available in PMC 2021 December 08.

Published in final edited form as:

Curr Opin Neurol. 2018 April ; 31(2): 134–139. doi:10.1097/WCO.0000000000000541.

Motor development and delay: advances in assessment of motor skills in autism spectrum disorders

Rujuta B. Wilson[a], **Peter G. Enticott**[b], **Nicole J. Rinehart**[b]

[a]UCLA Semel Institute of Neuroscience and Human Behavior, David Geffen School of Medicine, UCLA Division of Pediatric Neurology, Los Angeles, California, USA

[b]Deakin Child Study Centre, School of Psychology, Faculty of Health, Deakin University, Geelong, Victoria, Australia

Abstract

Purpose of review—Motor impairments in neurodevelopmental disorders, specifically autism spectrum disorder (ASD), are prevalent and pervasive. Moreover, motor impairments may be the first sign of atypical development in ASD and likely contribute to abnormalities in social communication. However, measurement of motor function in ASD has lagged behind other behavioral phenotyping. Quantitative and neurodiagnostic measures of motor function can help identify specific motor impairments in ASD and the underlying neural mechanisms that might be implicated. These findings can serve as markers of early diagnosis, clinical stratification, and treatment targets.

Recent findings—Here, we briefly review recent studies on the importance of motor function to other developmental domains in ASD. We then highlight studies that have applied quantitative and neurodiagnostic measures to better measure motor impairments in ASD and the neural mechanisms that may contribute to these abnormalities.

Summary—Information from advanced quantitative and neurodiagnostic methods of motor function contribute to a better understanding of the specific and subtle motor impairments in ASD, and the relationship of motor function to language and social development. Greater utilization of these methods can assist with early diagnosis and development of targeted interventions. However, there remains a need to utilize these approaches in children with neurodevelopmental disorders across a developmental trajectory and with varying levels of cognitive function.

Keywords

autism spectrum disorder; motor control; motor function

INTRODUCTION

The development of the motor system is critical for an individual to engage with the environment. As a child gains the ability to crawl, point, and ambulate, new opportunities

Correspondence to Rujuta B. Wilson, MD, 760 Westwood Plaza, Room A7-420, Los Angeles, CA 90095, USA. Tel: +1 310 825 1746; fax: +1 310 206 4245; rbhatt@mednet.ucla.edu.

Author Manuscript Author Manuscript Author Manuscript Author Manuscript

arise for social interactions with caregivers and peers [1]. Neurodevelopmental disorders (NDDs) are a heterogeneous group of conditions that are characterized by delays or abnormalities in a variety of developmental domains, including delays in motor skills [Diagnostic and Statistical Manual of Mental Disorders Fifth Edition (DSM-5)]. Within the group of NDDs, autism spectrum disorder (ASD) is diagnosed based on core impairments in social communication skills. However, motor impairments are particularly prevalent in ASD, and they can be the first sign of atypical development [2,3]. With advances in genetic testing, there has also been an increased identification of copy number variants and single gene disorders that confer elevated risk for ASD [4,5■■]. Motor impairments are often the first sign of abnormal development in these genetic variants and may be more common in children with syndromic forms of ASD [5■■,6]. Thus, the identification of early motor delays might be indicative of an individual at higher risk for a genetic disorder. Despite their clinical relevance, quantification of motor skills in ASD has been hampered by the use of standardized assessments that mostly capture developmental milestones and rely on an individual's ability to understand complex tasks [7,8]. These assessments often lead to results that do not adequately capture a child's motor abilities or impairments. This has led researchers to develop and utilize quantitative measures of motor function to better identify motor impairments in ASD to aid in earlier diagnosis and development of individualized interventions. In this review, we briefly discuss new findings on the relationship between motor skills, core ASD features, and cognitive function, and then review recent advances in quantitative and measures of motor function in ASD.

RELATIONSHIP OF MOTOR FUNCTION TO OTHER DEVELOPMENTAL DOMAINS

The development of motor function is linked to a child's capacity for language, cognitive, and social development, and may serve as an indication of emergent developmental psychopathology [1,9]. Retrospective studies of infants at high risk for ASD or with a confirmed diagnosis of ASD report the emergence of motor impairments before the more salient social-communicative impairment has been formally diagnosed. It is well accepted that early emergence of motor impairments has a downstream impact on key aspects of social and communicative development, for example, impairing a child's ability to gesture, and interact with other children in play [1,2,10].

Longitudinal studies reveal that the connection between motor, language, and higher-level cognitive impairment continues into childhood. In the school-age period, when children may experience higher developmental demands, studies have shown a relationship between motor impairments and disturbances in emotional and behavioral functioning, as measured on the Developmental Behavior Checklist. One explanation for this association is that children who experience greater motor problems may experience more adverse life events, for example, being excluded from school yard games and more trouble with academic tasks such as handwriting, thus leading to the higher levels of psychopathology [11].

A recent study on high-risk infant siblings (defined by having a sibling with ASD) examined whether advances in sitting, and also prone locomotion, are related to communicative

Author Manuscript Author Manuscript Author Manuscript Author Manuscript

development [12■■]. This longitudinal study included 37 high-risk infants, with gross motor skills assessed at monthly intervals from 5 to 14 months using the Alberta Infant Motor Scale (AIMS), which is a standardized observational measure of prone postures utilized in sitting and locomotion [13]. The age of onset of verbal and nonverbal communication was also recorded. Motor delays were observed across all observations, with the majority of participants exhibiting delays by 5 and 6 months of age. Motor development recorded monthly on the AIMS was related to emergence of both verbal and nonverbal communicative milestones. As the authors hypothesized, the ability to sit unsupported relates to both verbal (reduplicative babbling) and nonverbal communication (show gesture onset), whereas prone locomotion related to nonverbal communication milestones (show and point gesture). The authors state that acquiring independent sitting increases the use of manual movements to engage with people and also allows an infant to coordinate behaviors, such as eye contact with multiple individuals [12■■]. Therefore, in addition to the relationship of motor skills with other domains (such as language and communication), developments in gross motor skills can serve as the building blocks for more complex social and behavioral interactions. Moreover, there can be lifelong implications if motor development is disrupted.

Another study that evaluated high-risk infant siblings (defined as having a sibling with ASD) examined the relationship between motor skills and executive functioning, which is a set of higher-level cognitive functions including attention, working memory, and planning. This study compared the relationship of motor skills and executive functioning in high-risk infants (both those who went on to receive an ASD diagnosis and those who did not) and low-risk infants (defined as a child without a sibling or family history of ASD) at 12 and 24 months of age. Motor function was assessed using the Mullen Scales of Early Learning (MSEL) – a standardized measure of cognitive development for children from birth to 68 months [14]. Although no group differences were seen at 12 months, at 24 months, all high-risk infants demonstrated worse working memory and response inhibition compared to low-risk infants. In addition, in all groups, worse gross motor skills were associated with worse response inhibition [15■■].

The mounting research evidence connecting early motor impairment to poorer global developmental outcomes for children at high risk for ASD supports the importance of better understanding motor impairments that might be specific to ASD and when these impairments emerge. Given the heterogeneity of ASD and the discovery of genetic syndromes highly penetrant for ASD, quantitative and neurodiagnostic measures of motor may shed light on the individual variability of motor function in these disorders.

QUANTITATIVE MEASURES OF MOTOR FUNCTION IN AUTISM SPECTRUM DISORDER

Quantitative tools of motor function often use kinetic and kinematic analysis to capture specific spatiotemporal variables of motor function (e.g. gait analysis, three-dimensional motion capture analysis, digitized tablets). ‘Kinetics’ refers to the study of forces that cause motion such as torque, gravity, and friction. ‘Kinematics’ is the study of movement such

Author Manuscript Author Manuscript Author Manuscript Author Manuscript

as displacement in time and velocity. These tools have identified gross and fine motor impairments that differentiate individuals with ASD from other groups [16,17,18■]

Motor impairments in ASD are often present beyond early childhood and can affect both gross and fine motor domains such as balance and manual dexterity [3]. These persistent deficits can affect school-based activities, which can influence cognitive and academic performance. For example, measures of handwriting ability can shed light on multiple motor domains, such as grip strength and manual dexterity, and they provide useful information on a frequently employed school-based activity. A recent study utilized an advanced quantitative digitized tablet to evaluate kinematic variables of handwriting (tortuosity, speed, size) and its relationship to attention and ASD core symptomology in school-aged children with ASD. The task was designed to minimize additional cognitive and linguistic processes, which can confound studies of ASD [19■■]. Participants were also evaluated using the Movement Assessment Battery for Children-2 (MABC-2), a standardized measure of motor function examining three domains – manual dexterity, balance, and aiming and catching [20]. Three main findings were highlighted in the study: caregiver report indicated greater handwriting difficulties in children with ASD compared to typically developing age-matched peers; handwriting performance in the ASD group was characterized by significantly poorer writing quality and speed; and greater severity of ASD, attention, and motor symptoms were correlated with reduced handwriting performance and greater difficulties in functional handwriting performance [19■■]. However, one of the most salient points of the study was the value and feasibility of a reliable, easy, and quantitative (rather than qualitative) assessment of handwriting performance.

Similar to the evaluation of handwriting skills, there has been use of kinematic analysis for evaluate of gait. Studies utilizing gait analysis have identified differences in stride width, velocity, and stride length in children with ASD compared to typically developing children [21,22,23■]. These findings provide more clarity to previous qualitative descriptions of gait in ASD such as ‘clumsy, rigid, and wide-based’ [24,25]. A recent study using three-dimensional motion capture to evaluate gait function in ASD has shown asymmetry of gait, which is thought to be a marker of pathologic motor development. Kinetic and kinematic gait data were obtained from children 5–12 years of age with ASD using a Vicon three-dimensional motion capture system. Unlike previous studies, the authors used point-to-point analysis to evaluate data across a gait cycle rather than in discrete time points. The results showed significant asymmetry in joint positions (kinematic data) and nearing significance in right and leg joint force (kinetic data). Additionally, the analysis allowed evaluation at different points during the gait cycle, which can indicate greater dysfunction in positioning of the hips, knees, or ankles. The authors noted that although asymmetry might not always be detrimental, persistent asymmetry in gait starting from childhood could be problematic. When asymmetry is present, the contralateral leg is required to compensate in position and force, and this can place an individual at greater risk for injury [26■]. Abnormalities in gait symmetry can also lead to difficulties in social play-based activities and sports, creating a barrier for children with ASD to participate in such activities with their peers. This work also provides clearer targets for motor intervention.

Author Manuscript Author Manuscript Author Manuscript Author Manuscript

These quantitative measures of motor function have increased our knowledge of more specific motor impairments in ASD and have even led researchers to use these findings to hypothesize that impairments in motor could be secondary to disruptions in cerebellar or fronto-striatal networks [16,27]. The more recent utilization of neurodiagnostic measures, such as electroencephalography (EEG), MRI, and transcranial magnetic stimulation (TMS), has provided early insights into more specific abnormal neural networks leading to motor impairments in ASD [28■,29■,30■■,31■■].

NEURODIAGNOSTIC MEASURES OF MOTOR FUNCTION

Studies of neural mechanisms used in conjunction with standardized and quantitative motor measures are essential to parse out the heterogeneity of ASD and identify targets for behavioral and pharmacologic interventions for motor impairments.

Electroencephalography offers an economical and noninvasive method for investigating motor-related neural activity, including neural connectivity [32]. Oscillatory electrical activity, as captured by EEG, reflects aspects of neural excitation and inhibition, with the latter primarily modulated by GABAergic processes. Altered brain oscillatory activity has been implicated in ASD (for review, see [33]). In motor output areas, the modulation (suppression) of beta band oscillations (typically defined as 13–30 Hz) has emerged as a prominent signal, particularly elicited during motor specific actions. Beta oscillations might indicate ongoing sensorimotor integration, coordination, and motor preparation, as attenuation of beta oscillations are linked to faster onset of movement [34]. Quantifying modulations of beta oscillations during task-dependent motor activities in individuals with ASD can provide valuable information regarding potential aberrant cortical networks that might be contributing to the motor dysfunction.

In a recent study, EEG was used to evaluate the role of oscillatory changes during a praxis motor control task in children with ASD from 8 to 13 years of age [31■■]. The study chose to evaluate praxis, because this motor domain represents the performance of complex, skilled gestures that are used in functional skills and communication. EEG was recorded while the patients performed a praxis paradigm made up of pantomiming 10 common tools. Individuals with ASD displayed reduced task-related EEG power modulation during performance on the praxis task, which suggests that dyspraxia in ASD might be associated with decreased activity in the frontal-parietal praxis network. The authors also found a correlation between decreased left central beta band desynchronization and autism severity (defined from Autism Diagnostic Observation Scale severity scores). These findings indicate aberrant neural physiology associated with motor impairments in ASD, and offers a potential brain-based marker that can be measured with introduction of interventions [31■■].

Imaging studies using MRI, functional MRI (fcMRI), and diffusion-tensor imaging (DTI)/diffusion tractography/diffusion-weighted images have identified atypical patterns of structural brain growth in ASD [35]. The use of imaging studies in conjunction with behavioral measures of motor function can allow evaluation of the neurobiology underlying motor development.

Author Manuscript Author Manuscript Author Manuscript Author Manuscript

As noted earlier in this review, studies of infants at risk for ASD have primarily utilized behavioral measures to identify differences in motor development. A recent study used resting state fcMRI to identify functional brain networks associated with walking and gross motor skills in infants at low and high risk for ASD. In all, 187 infants at 12 and 24 months of age underwent gross motor assessments through the Mullen Scales of Early Learning (MSEL) and brain MRI. Scores for walking and gross motor function were analyzed in relation to network level functional connectivity based on fcMRI data acquired from infants and toddlers during natural sleep. The authors adapted a statistical method termed enrichment analysis to use a brain-wide approach to identify networks with a significantly increased density of connections strongly related to the studies of walking and gross motor behaviors. The findings indicated that subsets of infant/toddler brain networks show strong relationships of functional connectivity to walking and gross motor function, and the profile of these brain networks differs at 12 and 24 months. Additionally, these network profiles involve both positive and negative brain–behavior relationships, which implies that increases and decreases in network level connectivity may underlie the developmental progression of walking and gross motor function during this age range. The description of these brain networks of early gross motor development can aid in informing neural systems contributing to typical and atypical motor outcomes and also potentially aid in differentiating neurodevelopmental disorders associated with motor abnormalities [36■■].

Studies of neuroimaging to better identify neural mechanisms of motor dysfunction in adults with ASD has been more frequently utilized compared to younger populations. A recent study of adults with high functioning ASD combined the use of diffusion tractography and a behavioral measure of fine motor skill performance [37■■]. It was found that participants with ASD had slower performance on the Purdue Pegboard test compared to typically developing adults. Additionally, diffusion tractography investigating primary motor cortex (M1) and somatosensory cortex (S1) connections showed decreased fractional anisotropy and increased perpendicular diffusivity, which has been seen in association with abnormalities of white matter tract structure, reduced tract coherence and organization, and reduced myelination. It is thought that these white matter abnormalities might underpin slower and worse performance on the Purdue Pegboard test. This study provides direct support of the role of the connections between S1, M1, and fine motor skill performance, and supports the potential development of therapeutic approaches due to the relationship of S1 input to M1 in long term potentiation [37■■]

FUTURE DIRECTIONS AND CONCLUSION

As we move forward in the assessment of motor function in ASD it is imperative the field continue to employ these quantitative (both behavioral and neurodiagnostic) measures. This study has highlighted the advances in assessment of motor function in ASD and the contribution these assessments have made in better understanding more specific and subtle motor impairments in ASD and the underlying pathophysiology leading to these impairments.

Despite evidence for definitive motor dysfunction in ASD, studies of motor function in ASD, however, face some significant limitations, which include lack of large samples

Author Manuscript Author Manuscript Author Manuscript Author Manuscript

of children with ASD and varying levels of behavioral and cognitive functioning; few studies evaluating children with ASD across development to examine emergence of motor impairment and changes over time; few studies that evaluate the impact of genetic cause, ASD severity, and prevalent behavioral comorbidities (attention deficit hyperactivity disorder, intellectual disability, irritability) on the manifestation of motor impairments. Quantitative measures of motor function can alleviate the cognitive and behavioral requirements of most standardized motor assessments and assess individuals with ASD across a lifespan. These qualities allow the study of a more heterogeneous sample of individuals with ASD. Additionally, future studies should utilize these measures to compare motor impairments in other NDDs to ASD, to establish the degree of specificity of certain motor impairments in ASD.

Recently, the literature has recognized how motor impairments in ASD not only affect other developmental domains but can also lead to reduced participation in physical activity and subsequent predisposition to poorer health outcomes [38■]. Evidence-based early intervention programs that target social and behavioral difficulties in children with ASD have shown to facilitate long-term improvements in these areas [39]. A recent systematic review highlighted the benefits of various physical activity interventions for children with ASD below 16 years of age. The study found that jogging, horseback riding, martial arts, swimming, and yoga/dance can result in improvements to numerous behavioral outcomes. These outcomes include stereotyped behaviors, social–emotional functioning, cognition, and attention [40]. Another study evaluated the benefits of an Australian Football League program adapted for children with ASD. Children enrolled in the program for 1.5 h a week over a total of 11 weeks. Although there was not significant change on the objective motor assessment, standardized parent questionnaire indicated significant improvement in child object control skills. Parents also noted improvements in coordination and social skills [41]. The positive results of these studies highlight the critical need to develop evidence-based motor and physical activity interventions for individuals with ASD.

As we begin to identify specific motor impairments in ASD and the timing of emergence of these impairments, we can begin to develop timely, individualized interventions and community-based services that support these individuals and improve overall neurodevelopmental outcomes and long-term functioning.

Financial support and sponsorship

Dr Wilson is funded by the National Institutes of Health.

Professor Enticott is funded by a Future Fellowship from the Australian Research Council (FT160100077). He also receives funding from the Brain and Behavior Research Foundation and Fererro.

The work was supported by the Department of Psychiatry at UCLA and the Centre for Social and Early Emotional Development (SEED), Deakin University.

Conflicts of interest

Dr Wilson has no conflicts of interest to disclose.

Prof. Enticott and Professor Rinehart receive funding from the Ferrero Group, Australia as part of its Kinder + Sport pillar of Corporate Social Responsibility initiatives to promote active lifestyles among young people. Ferrero

Author Manuscript Author Manuscript Author Manuscript Author Manuscript

Group Australia had no role in this research including the collection, analysis, and interpretation of data; in writing of the manuscript; and in the decision to submit the article for publication.

REFERENCES AND RECOMMENDED READING

Papers of particular interest, published within the annual period of review, have been highlighted as:

■ of special interest

■■ of outstanding interest

1. Iverson JM. Developing language in a developing body: the relationship between motor development and language development. J Child Lang 2010; 37:1–25. [PubMed: 19323859]
2. Esposito G, Venuti P, Maestro S, Muratori F. An exploration of symmetry in early autism spectrum disorders: analysis of lying. Brain Dev 2009; 31: 131–138. [PubMed: 18534798]
3. Fournier KA, Hass CJ, Naik SK, et al. Motor coordination in autism spectrum disorders: a synthesis and meta-analysis. J Autism Dev Disord 2010; 40:1227–1240. [PubMed: 20195737]
4. Jeste SS, Geschwind DH. Clinical trials for neurodevelopmental disorders: at a therapeutic frontier. Sci Transl Med 2016; 8:1–4.
5 ■■. Bishop SL, Farmer C, Bal V, et al. Identification of developmental and behavioral markers associated with genetic abnormalities in autism spectrum disorder. Am J Psychiatry 2017; 174:576–585. [PubMed: 28253736] This study highlights theprevalence ofmotorfunction in genetic disorders associated with ASD and relationship of gait dysfunction to the yield of genetic testing.
6. Distefano C, Gulsrud A, Huberty S, et al. Identification of a distinct developmental and behavioral profile in children with Dup15q syndrome. J Neurodev Disord 2016; 8:19. [PubMed: 27158270]
7. Staples KL, Reid G. Fundamental movement skills and autism spectrum disorders. J Autism Dev Disord 2010; 40:209–217. [PubMed: 19685284]
8. Allen KA, Bredero B, Van Damme T, et al. Test of gross motor development-3 (TGMD-3) with the use of visual supports for children with autism spectrum disorder: validity and reliability. J Autism Dev Disord 2017; 47:813–833. [PubMed: 28091840]
9. Karasik LB, Tamis-lemonda CS, Adolph KE. Transition from crawling to walking and infants' actions with objects and people. Child Dev 2011; 82:1199–1209. [PubMed: 21545581]
10. Bhat AN, Landa RJ, Galloway JC, et al. Current perspectives on motor functioning in infants, children, and adults with autism spectrum disorders. Phys Ther 2011; 91:1116–1129. [PubMed: 21546566]
11. Papadopoulos N, Mcginley J, Tonge B, et al. Motor proficiency and emotional / behavioural disturbance in autism and Asperger ' s disorder: another piece of the neurological puzzle? 2011. Autism 2012; 16:627–640.
12 ■■. Lebarton ES, Iverson JM. Infant behavior and development full length article associations between gross motor and communicative development in at-risk infants. Infant Behav Dev 2016; 44:59–67. [PubMed: 27314943] This study highlights the relationship of motor development to social communication
13. Piper M, Darrah J. Motor Assessment of the Developing Infant. Philadelphia, PA: Saunders Publishing; 1994.
14. Mullen EM. Mullen Scales of Early Learning. Circle Pines, MN: American Guidance Service; 1995.
15 ■■. John TS, Estes AM, Dager SR, et al. Emerging executive functioning and motor development in infants at high and low risk for autism spectrum disorder. Front Psychol 2016; 7:1016. [PubMed: 27458411] This study highlights the relationship of motor impairments and more complex cognitive development.
16. Rinehart NJ, Tonge BJ, Iansek R, et al. Gait function in newly diagnosed children with autism: cerebellar and basal ganglia related motor disorder. Dev Med Child Neurol 2006; 48:819–824. [PubMed: 16978461]

Author Manuscript Author Manuscript Author Manuscript Author Manuscript

17. Cook JL, Blakemore SJ, Press C. Atypical basic movement kinematics in autism spectrum conditions. Brain 2013; 136:2816–2824. [PubMed: 23983031]

18 ■. Anzulewicz A, Sobota K, Delafield-butt JT. Toward the autism motor signature: gesture patterns during smart tablet gameplay identify children with autism. Sci Rep 2016; 6:31107. [PubMed: 27553971] This study demonstrates the ability to use a quantitative tablet to evaluate fine motor function in young children with ASD.

19 ■■. Grace N, Gregory P, Beth E, et al. Do handwriting difficulties correlate with core symptomology, motor proficiency and attentional behaviours? J Autism Dev Disord 2017; 47:1006–1017. [PubMed: 28083779] This study utilizes a quantitative measure of handwriting to identify my subtle and specific impairments in handwriting in children with ASD compared to typically developing children.

20. Henderson SE, Sugden DA, Barnett AL. Movement assessment battery for children (2nd ed.). London: Harcourt Assessment; 2007.

21. Kindregan D, Gallagher L, Gormley J. Gait deviations in children with autism spectrum disorders: a review. Autism Res Treat 2015; 2015:741480. [PubMed: 25922766]

22. Lim BO, O'Sullivan D, Choi B-G, Kim M-Y. Comparative gait analysis between children with autism and age-matched controls: analysis with temporal-spatial and foot pressure variables. J Phys Ther Sci 2016; 28:286–292. [PubMed: 26957776]

23 ■. Dufek JS, Eggleston JD, Harry JR, Hickman RA. A comparative evaluation of gait between children with autism and typically developing matched controls. Med Sci (Basel) 2017; 5:. doi: 10.3390/medsci5010001.This study utilizes three-dimensional motion capture to evaluate multiple gait trials of children with ASD compared to age matched typically developing children.

24. Kanner L. Autistic disturbances of affective contact. Nerv Child 1943; 2:217–250.

25. Wing L. Asperger's syndrome: a clinical account. Psychol Med 1981; 11:115–129. [PubMed: 7208735]

26 ■. Eggleston D, Harry JR, Hickman RA, Dufek JS. Analysis of gait symmetry during over-ground walking in children with autism spectrum disorder. Gait Posture 2017; 55:162–166. [PubMed: 28458147] This study utilizes three dimensional motion capture to evaluate the entire gait cycle in children with ASD.

27. Mostofsky SH, Dubey P, Jerath VK, et al. Developmental dyspraxia is not limited to imitation in children with autism spectrum disorders. J Int Neuropsychol Soc 2006; 12:314–326. [PubMed: 16903124]

28 ■. Jarczok TA, Fritsch M, Kroger A, et al. Maturation of interhemispheric signal propagation in autism spectrum disorder and typically developing controls: a TMS-EEG study. J Neural Transm (Vienna) 2016; 123:925–935. [PubMed: 27177879] This study utilizes two neurodiagnostic measures to evaluate interhemispheric connections and better understand development and maturation of the corpus callosum in adolescents with ASD.

29 ■. Kirkovski M, Rogasch NC, Saeki T, et al. Single pulse transcranial magnetic stimulation: electroencephalogram reveals no electrophysiological abnormality in adults with high-functioning. J Child Adolesc Psychopharmacol 2016; 26:606–616. [PubMed: 27284688] This study utilizes two neurodiagnostic measures to evaluate cortical function and connectivity in adults with ASD.

30 ■■. Floris DL, Barber AD, Nebel MB, et al. Atypical lateralization of motor circuit functional connectivity in children with autism is associated with motor deficits. Mol Autism 2016; 7:35. [PubMed: 27429731] This study utilized functional MRI to study whether the functional motor execution network shows an atypical pattern of hemispheric specialization in ASD.

31 ■■. Ewen JB, Lakshmanan BM, Pillai AS, et al. Decreased modulation of EEG oscillations in high-functioning autism during a motor control task. Front Hum Neurosci 2016; 10:198. [PubMed: 27199719] This study utilizes EEG to evaluate if there is abnormal oscillatory modulation during a praxis task, which is a motor domain that has been frequently implicated in the ASD phenotype.

32. Jeste SS, Frohlich J, Loo SK. Electrophysiological biomarkers of diagnosis and outcome in neurodevelopmental disorders. Curr Opin Neurol 2015; 28:110–116. [PubMed: 25710286]

Author Manuscript Author Manuscript Author Manuscript Author Manuscript

33. Mohammad-Rezazadeh I, Frohlich J, Loo SK, Jeste SS. Brain connectivity in autism spectrum disorder. Curr Opin Neurol 2016; 29:137–147. [PubMed: 26910484]

34. Khanna P, Carmena JM. Beta band oscillations in motor cortex reflect neural population signals that delay movement onset. Elife 2017; 6:1–31.

35. Mahajan R, Mostofsky SH. Neuroimaging endophenotypes in autism spectrum disorder. CNS Spectr 2015; 20:412–426. [PubMed: 26234701]

36 ■■. Marrus N, Eggebrecht AT, Todorov A, et al. Walking, gross motor development, and brain functional connectivity in infants and toddlers. Cereb Cortex 2018; 28(2):750–763. [PubMed: 29186388] This study utlizes functional MRI to evaluate the relationship between functional connectivity and the emergence of gross motor function

37 ■■. Thompson A, Murphy D, Acqua FD, et al. Archival report impaired communication between the motor and somatosensory homunculus is associated with poor manual dexterity in autism spectrum disorder. Biol Psychiatry 2017; 81:211–219. [PubMed: 27639500] This study utilizes diffusion tensor imaging to evaluate sensory input to the primary motor cortex from the somatosensory cortex and the possibility of alternations in this network leading to fine motor impairments in adults with ASD.

38 ■. Jones R, Downing K, Rinehart N. A systematic review of physical activity and sedentary behavior in children with Autism. PLoS One 2017; 12:e0172482. [PubMed: 28245224] This review highlights the prevalence of decreased physical activity in individuals with ASD and how this can lead to sedentary behaviors and contribute to harmful health outcomes.

39. Makrygianni MK, Reed P. A meta-analytic review of the effectiveness of behavioural early intervention programs for children with Autistic Spectrum Disorders. Res Autism Spectr Disord 2010; 4:577–593.

40. Bremer E, Crozier M, Lloyd M. A systematic review of the behavioural outcomes following exercise interventions for children and youth with autism spectrum disorder. Autism 2016; 20:899–915. [PubMed: 26823546]

41. May Tamara. Barnett Lisa. Hinkley Trina, et al. We’re doing afl auskick as well’: experiences of an adapted football program for children with autism. J Mot Learn Dev 2016; 1–29; https://journals.humankinetics.com/doi/abs/10.1123/jmld.2016-0055.

Author Manuscript Author Manuscript Author Manuscript Author Manuscript

KEY POINTS

- Motor impairments are prevalent in autism spectrum disorder and are related to overall development.
- Quantitative measures of motor function can aid in identifying specific and subtle motor impairments in ASD.
- Neurodiagnostic measures of motor function can better elucidate aberrant underlying neural mechanisms contributing to motor impairments in ASD.
- Early identification of motor impairments in ASD can aid in early intervention and improved long term functioning.