

RESEARCH ARTICLE

Abnormal Gait Patterns in Autism Spectrum Disorder and Their Correlations with Social Impairments

Linlin Gong, Yajie Liu, Li Yi , Jing Fang, Yisheng Yang, and Kunlin Wei 

Ground walking in humans is typically stable, symmetrical, characterized by smooth heel-to-toe ground contact. Previous studies on children with autism spectrum disorder (ASD) identified various gait abnormalities. However, they produced inconsistent findings, particularly for the occurrence of toe walking and gait symmetry between feet, owing to their reliance on retrospective reports, visual analysis of videos, or kinematic analysis of the gait. The present study examined gait functions in children with ASD using plantar pressure that quantified foot–ground interaction with high spatial and temporal resolutions. Fifty-eight 4–6-year-old children with ASD (12 low-functioning and 46 high-functioning autism) and 28 age-matched typically developed children walked straight 6 m at their preferred speed for 10 repetitions. We found that both ASD groups walked with more flat-footed contact pattern, more left–right asymmetry, and larger step-to-step variability than their controls. Furthermore, these abnormal gait characteristics were related to social impairments measured by the Autism Spectrum Quotient and Social Responsive Scale, supporting a close association between impaired motor coordination and core symptoms of autism. *Autism Res* 2020, 13: 1215–1226. © 2020 International Society for Autism Research, Wiley Periodicals, Inc.

Lay Summary: We examined gait functions among children with autism by measuring their foot plantar pressure during simple straight walking. Children with ASD walked with a characteristic foot-ground contact pattern with inappropriate contact forces and large step-to-step variability when compared with their age-matched controls. These walking abnormalities were dependent on their social impairments but independent from their intelligence, indicating a close relationship between atypical motor coordination and core symptoms of autism.

Keywords: autism; motor deficits; motor coordination; gait; social impairments

Introduction

Children with autism spectrum disorder (ASD) have various motor impairments, including deficits in gross and fine motor control [Fuentes, Mostofsky, & Bastian, 2009], impaired postural control [Dumas, McKenna, & Murphy, 2016; Jansiewicz et al., 2006; Travers, Powell, Klinger, & Klinger, 2013; Vanvuchelen, Roeyers, & De Weerd, 2007], alterations in motor planning [Dowd, McGinley, Taffe, & Rinehart, 2012; Rinehart, Bellgrove, et al., 2006], and abnormal motor coordination [Fournier, Hass, Naik, Lodha, & Cauraugh, 2010]. These motor impairments emerge as early as infancy [Esposito & Venuti, 2008; Flanagan, Landa, Bhat, & Bauman, 2012; Teitelbaum et al., 2004; Teitelbaum, Teitelbaum, Nye, Fryman, & Maurer, 1998], continually occur in childhood [Fournier et al., 2010] and adulthood [Dumas et al., 2016; Minshew, Sung, Jones, & Furman, 2004; Travers et al., 2013].

There is a growing interest in motor aspects of autism given their theoretical and practical significance [Cook, 2016; Fournier et al., 2010; Memari, Ghanouni, Shayestehfar, & Ghaheri, 2014]. Motor abnormalities emerge in early infancy, that is, postural asymmetry during lying, sitting, and crawling and delayed sitting and walking, and they have been proposed to serve as a first diagnostic marker for ASD [Esposito, Venuti, Apicella, & Muratori, 2011; Memari et al., 2014; Teitelbaum et al., 2004]. Furthermore, various motor deficits, for example, postural stability in quiet standing and the degree of kinematic atypical in a manual tracking task, are correlated with core autistic symptoms [Cook, Blakemore, & Press, 2013; Radonovich, Fournier, & Hass, 2013; Travers et al., 2013]. Researchers thus have proposed that motor impairments, which might lead to atypical representations of movements [Cook, 2016] and limitation of social interactions [Travers et al., 2013], contribute to the development of core autistic symptoms. Interestingly,

From the Beijing Key Laboratory of Behavior and Mental Health, School of Psychological and Cognitive Sciences, Peking University, Beijing, China (L.G., Y.L., L.Y., K.W.); Key Laboratory of Machine Perception (Ministry of Education), Peking University, Beijing, China (L.G., Y.L., L.Y., K.W.); Qingdao Autism Research Institute, Qingdao, Shandong, China (J.F., Y.Y.)

Received November 14, 2019; accepted for publication March 12, 2020

Address for correspondence and reprints: Kunlin Wei, Beijing Key Laboratory of Behavior and Mental Health, School of Psychological and Cognitive Sciences, Peking University, 5 Yiheyuan Road, Beijing 100871, China. E-mail: wei.kunlin@pku.edu.cn

Published online 1 May 2020 in Wiley Online Library (wileyonlinelibrary.com)

DOI: 10.1002/aur.2302

© 2020 International Society for Autism Research, Wiley Periodicals, Inc.

interventions targeting at improving motor skills have been found useful to improve not only motor skill proficiency [Bremer, Balogh, & Lloyd, 2015; Bremer & Lloyd, 2016; Ketcheson, Hauck, & Ulrich, 2017] but also social skills [Bremer & Lloyd, 2016]. Hence, the examination of motor functions among individuals with ASD becomes vital not only for understanding the etiology of autism but also for practical applications such as diagnosis and intervention.

There are a number of previous studies investigating the impairments of gait functions among individuals with ASD [Cook, 2016; Valagussa, Trentin, Signori, & Grossi, 2018]. However, inconsistent findings of the occurrence of toe walking and gait asymmetry have not been resolved. Toe walking in children with ASD has been widely reported [for a review, see Valagussa et al., 2018], but its reported percentage among children with ASD ranged from 15.2% [Uljarevic, Hedley, Alvares, Varcin, & Whitehouse, 2017] to 100% [Barrow, Jaworski, & Accardo, 2011], with a rough average of 30–40% as in various investigations [Shetreat-Klein, Shinnar, & Rapin, 2014; Valagussa, Trentin, Balatti, & Grossi, 2017]. The discrepancy among studies is at least partially caused by using subjective assessments of gait, such as parents' reports, video observation, and questionnaires. Without objective measures, researchers might find it hard to judge the presence of toe walking. For example, children with ASD exhibited reduced ankle dorsiflexion and knee extension at initial foot contact [Vilensky, Damasio, & Maurer, 1981] and toe-off [Nobile et al., 2011]. This atypical lower-limb movement pattern results in a so-called flat-footed walking pattern, which might be mislabeled as toe walking even if the foot contacts the ground with a regular heel contact. Previous quantitative studies have focused on kinematical analyses of joint angles without examining the foot-ground contact, leaving the inconsistency about toe walking unresolved.

The other unresolved aspect of gait among individuals with ASD is whether they have asymmetrical gait. Using retrospective analysis of video, researchers revealed left-right postural asymmetry during walking among infants at 20.2 ± 2.1 months old [Esposito & Venuti, 2008] and at 14.0 ± 1.4 months old who were later diagnosed as ASD [Esposito et al., 2011]. This gait asymmetry echoes with asymmetrical lying, sitting, and crawling among infants with ASD who were later diagnosed as ASD [Esposito, Venuti, Maestro, & Muratori, 2009]. The asymmetry in motor behaviors might be related to the abnormal lateralization in multiple brain networks among individuals with ASD [Cardinale, Shih, Fishman, Ford, & Muller, 2013]. However, gait asymmetry was so far only identified in autistic infants [Esposito & Venuti, 2008; Esposito et al., 2011]. A recent study found that 5–9-year-old children with ASD during straight walking did not exhibit asymmetry in kinematic measures such as cadence, stride length, and swing time [Chester & Calhoun, 2012]. However,

these general gait measures only quantify the kinematics of strides, which are usually symmetric for a short walk. Thus, whether gait asymmetry exists among children with ASD is still unanswered by visual inspection and simple kinematic analysis.

Plantar pressure measurements have been used to quantify the foot contact with the ground during gait for long [Cavanagh et al., 1997; Hennig & Rosenbaum, 1991; Hennig, Staats, & Rosenbaum, 1994]. Foot-ground interaction typically involves a smooth roll-off pattern, characterized by a gradual shift of the center of pressure (CoP) from heel to toe [Cavanagh et al., 1997; Hallemans, D'Août, De Clercq, & Aerts, 2003]. With foot pressure, toe walking can be clearly defined as an initial foot contact in the forefoot region (including toe and metatarsal regions) as opposed to the usual heel contact. The flat-footed contact pattern can be characterized by an earlier and longer contact of forefoot regions than the typical heel-to-toe contact pattern. Note, the earlier forefoot contact does not mean that the forefoot contacts the ground first. The gait asymmetry can be characterized by examining the correlation of force development between two feet. Notably, these quantifications of gait are hard to obtain by motion capture systems that are extensively used in previous studies. In the present study, we aimed to resolve the inconsistent findings on toe walking and gait asymmetry among children with ASD using plantar pressure during straight walking. Besides investigating possible differences from age-matched controls, we sought possible correlations between gait abnormalities and social impairments. Most motor deficits, previously identified as being related to social impairments among children with ASD, involve motor coordination. For instance, quiet standing involves coordinating muscles and body [Gatev et al., 1999; Suzuki, Nomura, Casadio, & Morasso, 2012], and manual tracking involves coordinating hand movement with a visual target [Vercher & Gauthier, 1988]. Straight walking, as simple as it appears, is about coordinating multiple body segments, especially those lower-limb joints. We thus hypothesize that atypical coordination during gait among children with ASD would correlate with their core symptoms.

Method

Participants

Children with ASD were divided into two groups based on their Full-Scale Intelligence Quotient (FSIQ): a high-functioning group (HFA, age range: 4.21–6.82 years, mean age: 5.39 ± 0.65 years, $n = 46$) with FSIQ above 80 and a low-functioning group (LFA, age range: 4.53–6.86 years, mean age: 5.77 ± 0.65 years, $n = 12$) with FSIQ below 80. The control group included 28 typically-developing (TD) children (age range: 4.60–6.81 years,

mean age = 5.69 ± 0.62) who matched the HFA group with age and FSIQ. The comparison between the HFA and the control group would help elucidate the autism-related effect while controlling for IQ. All children with ASD had been previously diagnosed by two professional pediatric clinicians based on Diagnostic and Statistical Manual of Mental Disorders—Fifth Edition [American Psychiatric Association, 2013]. We further confirmed the diagnosis of children with ASD by the Chinese version of the Autism Spectrum Quotient: Children's Version [AQ-Child; Auyeung, Baron-Cohen, Wheelwright, & Allison, 2008] and the Social Responsiveness Scale [SRS; Constantino & Gruber, 2002]. Parents completed the scales before the study. We measured children's IQ using the Chinese version of Wechsler Preschool and Primary Scale of Intelligence—Forth Edition [Wechsler, 2014]. All descriptions of participant characteristics are listed in Table 1.

Ethical approval for this study was obtained from the Ethical Committee of School of Psychological and Cognitive Sciences at Peking University. We obtained children's oral consent and parents' written consent before children's participation.

Procedure

Children were instructed to walk barefoot on a 6-m long carpet for 10 trials at self-spaced speed. A plantar pressure mat (RsScan, Inc.) was placed embedded in the middle of the carpet; thus, the mat and the carpet had the same height. The pressure mat has a size of 1 m $\times$ 0.4 m with a sensor density of about 2.7/cm². Each sensor sizes 5 mm (medial-lateral) $\times$ 7 mm (anterior-posterior). The sample rate of the pressure measurement was 100 Hz. Children were encouraged to walk and look straight ahead while fixating a 29.7 cm $\times$ 21 cm printed paper cross placed at the end of the walkway. The paper cross was hung on wooden support with a height of about 0.9 m. For children who could not focus on the paper cross, they were encouraged to fixate their mother or father standing at

the end of the walkway. Formal data collection started after several familiarization trials. The starting position was adjusted for each participant to make it more likely that the pressure mat can measure two footprints on a single trial. A trial was valid if (a) at least two complete footprints were collected, (b) children remained their fixation on the target during walking, and (c) they did not shuffle their feet to aim for the pressure mat during walking.

Data Analysis

Typical foot roll-off pattern during walking involves a smooth posterior-to-anterior weight shift, indicated as a progressive shift of foot pressure from the heel to the toe (Fig. 1A). This shift can be shown as the CoP "enters" the foot around the heel, traveled longitudinally along the foot, and "exits" the foot at the toe. We defined toe walking as touching the ground with the forefoot first, as opposed to typical heel contact. The frequency of toe walking occurrence was calculated. To characterize the possible flat-footed walking pattern, we calculated the traveling length of CoP (CoP_Y) along the longitudinal axis of the foot, normalized by each individual's foot length. CoP_Y was computed by taking the difference between the initial and the end position of CoP in the anterior-posterior axis of the foot divided by the individual's foot length. CoP_Y will be smaller when walking flat-footed than walking with typical foot roll-off. To obtain the anterior-posterior axis of the foot, we first calculated the foot progression angle, that is, the angle between the midline of the footprint and the walking direction, for each trial. The progression angle direction serves as the anterior-posterior axis of the foot (Y-axis), and its perpendicular direction is defined as the mediolateral axis of the foot (X-axis). The two-dimensional CoP trajectory was defined in this coordinate system.

We also analyzed the force development of the foot during a step (Fig. 1). The total force and the regional force within the forefoot and hindfoot were analyzed as a

Table 1. Characteristics of Participants

	LFA, <i>M</i> (SD)	HFA, <i>M</i> (SD)	TD, <i>M</i> (SD)	<i>F</i> -value	<i>P</i>	Post hoc
<i>N</i>	12	46	28	N/A	N/A	N/A
Male (female)	10 (2)	42 (4)	26 (2)	N/A	N/A	N/A
Age (years)	5.77 (0.66)	5.38 (0.66)	5.65 (0.59)	2.517	0.087	N/A
FSIQ						
Verbal IQ	67.08 (10.41)	107.72 (19.54)	115.25 (11.78)	38.42	<0.001	LFA < HFA ~ TD ^a
Performance IQ	69.42 (7.81)	108.93 (14.45)	108.93 (10.35)	51.64	<0.001	LFA < HFA ~ TD ^a
AQ	97.33 (9.13)	94.17 (14.31)	64.29 (10.02)	57.22	<0.001	LFA ~ HFA > TD ^a
SRS	112.08 (15.41)	101.24 (20.87)	53.46 (16.32)	62.24	<0.001	LFA ~ HFA > TD ^b

Note. < denotes significant decrease, > denotes significant increase, and ~ denotes no significant difference for post hoc pairwise comparisons.

^aCorrected by Dunnett's T3 for group comparisons.

^bCorrected by Bonferroni correction.

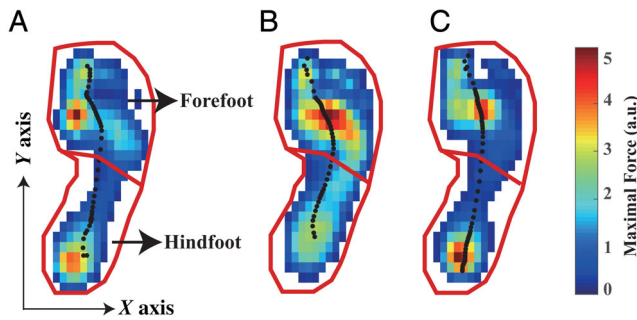


Figure 1. Exemplary foot pressure and CoP from three typical participants. (A) LFA, (B) HFA, (C) TD. Color denotes the maximal force recorded at different foot regions. Black dots denote the CoP trajectory during foot contact.

function of contact time. The time series data were normalized by contact duration via interpolating raw force measurements to 101 frames. The force for each region has a single peak; we thus calculated its time series of force, peak force (F_{peak}), time of peak force (T_{peak}), and contact duration (percentage of time relative to total foot contact time). The total force typically exhibits a double-peak pattern, with the first peak corresponding to initial foot contact and the second peak corresponding to foot push off the ground. The push-off phase is critical for walking as it provides the propelling force (Hayafune, Hayafune, & Jacob, 1999). We thus analyzed the time of second force peak ($T_{\text{second peak}}$, as a percentage of time relative to total foot contact time) and its associated force ($F_{\text{second peak}}$). For normalizing the individual differences in body weight and walking speed, all force-related variables were divided by the total force and the number of data frames [Wen et al., 2012]. After normalization, the dependent measures became unitless.

We evaluated gait asymmetry by correlating time-varying CoP between the left and right foot measured in the same walking trial. More symmetrical walking would yield a higher left–right correlation. The same correlation analysis was applied to force development in different foot regions. To measure the step-to-step variance, we computed the coefficient of variability (CV) of gait variables (GVs) across all footprints for each participant.

We first performed a two-way analysis of variance (ANOVA) with group as a between-subjects factor and foot (left vs. right) as a within-subject factor. When no significant main effect of foot or interaction was detected, one-way ANOVA was used to compare the group difference after combining the data from two feet. Otherwise, we performed one-way ANOVA on the left and right foot separately. Correlation coefficients were submitted to the Fisher's Z-transformation before one-way ANOVA. We examined the potential associations between specific GV (i.e., the timing of foot contact and forefoot force) and the variables about the severity of autism symptoms

(i.e., AQ and SRS scores) by using partial correlation with FSIQ as a covariate. These GV were related to abnormal gait characteristics among children with ASD, as stated by our study hypotheses. They included contact duration of the forefoot and initial contact time of forefoot (characterizing the flat-footed contact pattern), CV of contact duration and initial contact time of forefoot (characterizing step-to-step variability), and left–right correlation of forefoot force (characterizing left–right gait symmetry). Though most gait measures did not differ between the LFA and the HFA group (see below), we conducted the correlational analysis with all groups included since the unbalanced design with a small number of LFA participants might prevent us from finding significant group differences that were really there. All statistical analyses were performed using SPSS (version 24.0). Statistical significance was set at $\alpha = 0.05$. For multiple comparisons, Bonferroni or Dunnett's T3 corrections were used depending on the equality assumption.

Results

We observed extensive group differences in foot pressure measures, especially in foot–ground contact patterns and gait asymmetry during walking. Children with ASD walked with a flat-footed pattern though the occurrence of toe walking was not more frequent when compared with the control group. Furthermore, a detailed analysis of foot pressure indicated that children with ASD walked with more left–right asymmetry and more step-to-step variance. Importantly, we also found significant correlations between gait abnormalities and the severity of autism symptoms among our participants after controlling for IQ differences.

Temporal Pattern of Gait Measures

Both autistic and TD children seldom walked with initial toe contact. The occurrence of initial foot contact with the forefoot, including the metatarsal and the toe regions, was quite small. The majority of walking trials from the ASD groups had initial heel contact. Importantly, there was no group difference (Table 2).

Though toe walking is rare, children with ASD contacted the ground with a flat-footed pattern, as revealed by detailed plantar pressure analyses. We found a significant group difference in the initial position of CoP in Y-axis, which indicates how forward the pressure loading was upon the initial foot–ground contact ($F(2, 83) = 4.91$, $P = 0.009$, $\eta_p^2 = 0.107$, Fig. 2A). The post hoc pairwise comparison revealed that the HFA group started foot contact more anteriorly on foot (i.e., closer to the toe) than the TD group ($P = 0.015$). The LFA group did not differ from

Table 2. Gait Measures Associated with Toe Walking and Flat-Footed Contact Pattern

	LFA, <i>M</i> (SD)	HFA, <i>M</i> (SD)	TD, <i>M</i> (SD)	<i>F</i> -value	<i>P</i>	η_p^2	Post hoc
Percentage of initial forefoot contact	7% (0.15)	5% (0.07)	3% (0.12)	0.70	0.50	0.02	N/A
Percentage of initial hindfoot contact	93% (0.15)	95% (0.07)	97% (0.12)	0.70	0.50	0.02	N/A
Initial contact time of forefoot (100% contact duration)	5% (2%)	6% (3%)	9% (3%)	10.38	<0.001	0.24	TD > LFA ~ HFA ^a
<i>T</i> _{first peak} (100% contact duration)	25% (1%)	24% (1%)	24% (1%)	0.26	0.77	0.01	N/A
<i>F</i> _{first peak} (n.u.)	1.43 (0.04)	1.48 (0.05)	1.45 (0.03)	1.46	0.24	0.03	N/A
<i>F</i> _{first peak} of forefoot (n.u.)	0.32 (0.14)	0.37 (0.15)	0.28 (0.12)	2.98	0.06	0.07	N/A
<i>F</i> _{first peak} of hindfoot (n.u.)	1.08 (0.16)	1.12 (0.13)	1.13 (0.13)	0.63	0.54	0.15	N/A
<i>T</i> _{second peak} (100% contact duration)	65% (4%)	65% (5%)	70% (4%)	8.74	<0.001	0.17	TD > LFA ~ HFA ^a
<i>F</i> _{second peak} of forefoot (n.u.)	1.04 (0.15)	1.05 (0.14)	1.12 (0.09)	6.91	0.001	0.14	TD > LFA ~ HFA ^a
<i>F</i> _{second peak} of hindfoot (n.u.)	0.22 (0.21)	0.14 (0.14)	0.05 (0.07)	8.04	0.002	0.16	TD < LFA ~ HFA ^a

Note. < denotes significant decrease, > denotes significant increase, and ~ denotes no significant difference for post hoc pairwise comparisons.

^aCorrected by Bonferroni correction.

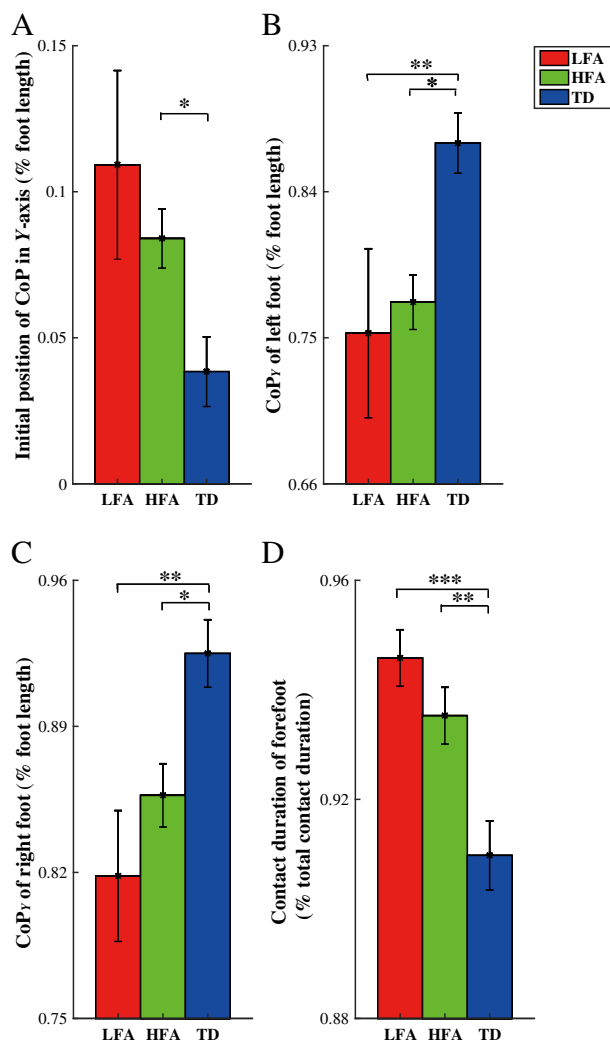


Figure 2. Group averages of GV measures associated with flat-footed walking among children with ASD. (A) The initial position of CoP on the Y-axis. (B, C) The traveling distance of CoP in Y-axis for the left foot and the right foot, respectively. (D) Contact duration of the forefoot (relative to total contact duration). Error bars denote SEM. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

the other two groups ($P = 0.84$ and $P = 0.16$, respectively) though they showed a similar trend as the HFA group.

Furthermore, the traveling distance of CoP (CoP_Y) was significantly smaller in the two autistic groups than in the TD group (for left foot, $F(2, 83) = 6.87$, $P = 0.002$, $\eta_p^2 = 0.142$, Fig. 2B; for right foot, $F(2, 83) = 6.36$, $P = 0.003$, $\eta_p^2 = 0.133$, Fig. 2C). Post hoc pairwise comparisons showed that two autistic groups had a shorter CoP_Y than the TD group for the left foot ($P = 0.018$ and $P = 0.003$, respectively) and the right foot ($P = 0.022$ and $P = 0.009$, respectively), while two autistic groups did not differ from each other (for left foot, $P = 1.00$; for right foot, $P = 0.62$). The small CoP_Y indicated that children with ASD did not have complete foot roll-off. Overall, their CoP traveled approximately 10% less for the left foot and 6% less for the right foot than TD children. We also found that for all groups, the right foot had a significantly larger CoP_Y than the left foot since the two-way ANOVA showed a significant main effect of foot ($F(1, 83) = 26.43$, $P < 0.001$, $\eta_p^2 = 0.242$). This was because our participants were all right-handed and used their right foot more to negotiate with the ground.

Besides the CoP, the foot contact duration also indicated the flat-footed pattern among children with ASD. First, the total contact duration had no group difference ($P = 0.56$), indicating that average walking speed did not differ between groups when walking at their preferred speed. However, contact duration of the forefoot significantly differ between groups ($F(2, 83) = 7.24$, $P = 0.001$, $\eta_p^2 = 0.15$, Fig. 2D). Post hoc comparison revealed that two groups with ASD had a significantly longer contact duration in the forefoot than the TD group ($P < 0.001$ and $P = 0.008$, respectively). The prolonged contact duration for the forefoot might be associated with the earlier initial contact of the forefoot. This earlier initial contact of the forefoot was found among both ASD groups when they were compared to the control group ($P < 0.001$, Table 2). We did not find a group difference for the hindfoot

($P = 0.93$). Putting together, results of CoP and contact duration indicated that children with ASD loaded the forefoot earlier with a shorter travel of CoP than the control group despite that they had initial foot-ground contact with the heel.

All our participants showed typical double peaks of the total force. We did not observe any group differences for the first force peak (Table 2). However, analyses of the second force peak revealed abnormal push off among children with ASD. The timing of this second peak ($T_{\text{second peak}}$) differed between groups ($F(2, 83) = 8.74$, $P < 0.001$, $\eta_p^2 = 0.174$, Fig. 3A). Post hoc comparisons revealed that both LFA and HFA groups reached the second peak force earlier than TD group ($P = 0.018$ and $P < 0.001$, respectively) without significant differences between two groups with ASD ($P = 1.00$).

Examining the force in the forefoot and the hindfoot separately at $T_{\text{second peak}}$, we found that the two ASD groups loaded less force on the forefoot but more force on the hindfoot. $F_{\text{second peak}}$ of both hindfoot and forefoot showed a significant group difference ($F(2, 83) = 8.04$ and 6.91 , $P = 0.001$ and 0.002 , $\eta_p^2 = 0.162$ and 0.143 , respectively; Fig. 3B,C). The hindfoot, supposed to lift off the ground during the push-off phase, produced less force. Post hoc comparison revealed that LFA and HFA groups had a larger loading on hindfoot than the TD group ($P = 0.052$ and $P < 0.001$, respectively), and they did not differ from each other ($P = 0.63$). In contrast, the forefoot, the major contributor of the propelling force for walking at the second peak time, produced less force among autistic children than among the TD children. Post hoc comparison found the significant differences between the two groups with ASD and the TD group only ($P = 0.028$ and $P = 0.002$ for LFA and HFA, respectively). These results indicated that children with ASD pushed their foot off the ground with less force with the forefoot and simultaneously loaded more on the

hindfoot, echoing the same flat-footed pattern as revealed by other measures.

Measures of Gait Asymmetry

We examined the gait symmetry by the left-right correlation of GV. The correlation coefficients between the left and right CoP were computed for each participant. Though left and right CoP were highly correlated among all participants, one-way ANOVA revealed significant group difference for the correlation of CoP in the Y direction ($F(2, 83) = 3.99$, $P = 0.022$, $\eta_p^2 = 0.088$). Post hoc pairwise comparison showed that both LFA (0.93 ± 0.05) and HFA groups (0.95 ± 0.05) walked with a lower level of symmetry than the TD group (0.98 ± 0.03 , $P = 0.036$ and $P = 0.097$). However, they did not differ from each other ($P = 0.80$).

The force development of foot regions also indicated gait asymmetry among children with ASD. We found that the forefoot regions, the predominant region for generating propelling force for walking, revealed a similar group difference on left-right correlation ($F(2, 83) = 6.07$, $P = 0.003$, $\eta_p^2 = 0.13$): both LFA (0.84 ± 0.11) and HFA (0.87 ± 0.07) groups showed a smaller correlation than the TD group (0.91 ± 0.05 , $P = 0.029$ and $P = 0.006$, respectively). Together, these results indicated that children with ASD walked more asymmetrically, as revealed by less similarity in CoP and force development between feet.

Step-to-Step Variability in Gait Measures

Unstable walking is characterized by large variance from step to step. For each GV, we computed their variability across steps using CV (Table 3). Significant larger step-to-step variabilities were found in autistic groups than in TD group for gait measures characterizing initial foot contact and contact duration, including initial contact position

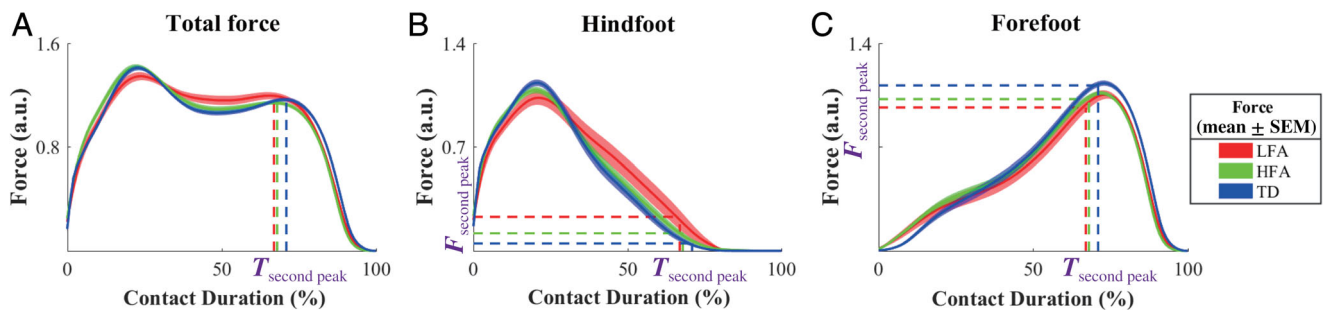


Figure 3. Force development as a function of contact time. (A) Total normalized force. Children with ASD reached the second peak force earlier than TD children. (B) Normalized force for the hindfoot. The force at the second peak time was larger in LFA and HFA than in TD. (C) Normalized force for the forefoot. Both LFA and HFA had earlier initial contact time and smaller force at the second peak time than TD. Lines denote subject averages and the color shade denotes SEM.

Table 3. CV of GV's Showing More Step-to-Step Variability Among Children with ASD

	LFA, <i>M</i> (SD)	HFA, <i>M</i> (SD)	TD, <i>M</i> (SD)	<i>F</i> -value	<i>P</i>	η_p^2	Post hoc
CoP _Y	0.16 (0.13)	0.19 (0.21)	0.07 (0.10)	4.33	0.018	0.09	TD < HFA ^a
Initial position of CoP in Y-axis	0.12 (0.08)	0.13 (0.11)	0.06 (0.07)	5.12	0.008	0.11	TD < HFA ^a
Contact duration	0.14 (0.05)	0.11 (0.05)	0.07 (0.03)	11.38	<0.001	0.22	TD < LFA ~ HFA ^b
<i>T</i> _{peak} of hindfoot	0.35 (0.14)	0.30 (0.14)	0.17 (0.07)	12.15	<0.001	0.23	TD < LFA ~ HFA ^b
<i>T</i> _{second peak}	0.11 (0.05)	0.12 (0.08)	0.06 (0.04)	7.78	0.001	0.16	TD < LFA ~ HFA ^b
<i>F</i> _{second peak} of forefoot	0.27 (0.12)	0.25 (0.12)	0.15 (0.06)	8.55	<0.001	0.17	TD < LFA ~ HFA ^b
Initial contact time of forefoot	0.69 (0.25)	0.73 (0.31)	0.41 (0.22)	10.81	<0.001	0.22	TD < LFA ~ HFA ^b

Note. < denotes significant decrease, > denotes significant increase, and ~ denotes no significant difference for post hoc pairwise comparisons.

^aCorrected by Dunnett's T3 for group comparisons.

^bCorrected by Bonferroni correction.

Table 4. Partial Correlation Between Each GV's and Scores of AQ and SRS

	All children				Children with ASD			
	Score of AQ		Score of SRS		Score of AQ		Score of SRS	
	<i>r</i>	<i>P</i>	<i>r</i>	<i>P</i>	<i>r</i>	<i>P</i>	<i>r</i>	<i>P</i>
Contact duration of forefoot	0.21	0.05	0.24	0.027	−0.12	0.36	−0.03	0.82
Initial contact time of forefoot	−0.30	0.006	−0.35	0.001	0.13	0.33	0.03	0.82
CV of contact duration	0.28	0.01	0.42	<0.001	−0.03	0.84	0.18	0.18
CV of initial contact time of forefoot	0.32	0.003	0.41	<0.001	−0.03	0.82	0.14	0.28
Correlation of forefoot force	−0.20	0.07	−0.31	0.004	0.09	0.51	−0.11	0.41

of CoP in Y-axis, initial contact time of forefoot and total contact duration. Similar increases in variance were found for the measures that characterize force loading in individual foot regions, including *T*_{peak} of the hindfoot, *T*_{second peak}, and *F*_{second peak} of the forefoot. Note, we observed more variance among children with ASD than TD children for all the significant group differences. Thus, children with ASD showed larger step-to-step variability in an extensive range of gait measures when compared with TD children.

Correlation Between Gait Impairments and Scores of AQ and SRS

When examining the correlation between gait characteristics and AQ/SRS scores, we focused on GV's about the timing of foot contact and forefoot force. We found that all these five GV's correlated significantly with SRS scores after controlling for IQ, with absolute values of correlation coefficients between 0.21 and 0.42 (Table 4). The same partial correlation analysis revealed that AQ scores were significantly correlated with three of the five variables. In fact, the correlation with the other two variables, contact duration of forefoot and correlation of forefoot force, was marginally significant. Their absolute correlation coefficients were between 0.21 and 0.32 with a moderate effect size. Importantly, the more abnormal the GV's, the more severe the autism symptoms. Partial correlation for different subscales of AQ and SRS were shown

in Table S1. The correlation between gait impairment and the severity of core symptoms seldom reach significance if only children with ASD were considered.

Discussion

Our study examined gait abnormality among children with ASD using plantar pressure measurements. Compared with age-matched controls, they walked with a flat-footed contact pattern shown by distinct CoP movements and contact duration of the forefoot. Interestingly, their forefoot did not contact the ground first, contradictory to previous reports of frequent toe walking among children with ASD. We also found increased gait asymmetry among children with ASD, as indicated by decreased correlation of CoP and force development between feet. They also showed increased step-to-step variance than the control group in various gait measures. Importantly, most variables characterizing the gait abnormalities correlated with the severity of autism symptoms after controlling the effect of IQ. Our findings thus suggest that abnormal motor coordination among children with ASD is associated with their core symptoms.

Previous studies reported the prevalence of toe walking among individuals with ASD [Barrow et al., 2011; Uljarevic et al., 2017; Valagussa et al., 2018]. However, toe walking has been either described as presence or absence [Ming, Brimacombe, & Wagner, 2007] or graded

by retrospective reports and observations [Accardo & Whitman, 1989]. The reliance on subjective evaluations probably leads to a wide range of reported occurrences across studies. For regular heel-to-toe walking, the initial foot contact coincides with a flexed hip, an extended knee, and a dorsiflexed ankle. However, individuals with ASD exhibit a reduced knee angle and an increased ankle angle at initial contact [Vilensky et al., 1981]. Thus, these kinematic deviances might make them prone to mislabels as toe walkers. With high-resolution plantar pressure measurements, we found that children with ASD do not toe walk but walk flat-footed. The unusual foot-ground contact is consistent with a previous report that children with ASD have a more dorsiflexed ankle at initial foot contact [Vilensky et al., 1981].

Other walking studies have found that children with ASD exhibit a reduced ankle flexion and knee flexion-extension at the toe-off phase of walking [Nobile et al., 2011; Vilensky et al., 1981] and a reduced range of motion of all lower-limb joints [Nobile et al., 2011]. While these kinematic differences lead to the impression that individuals with ASD walk with a more “clumsy” and “ataxic” gait [Fournier et al., 2010], they are consistent with the flat-footed contact pattern as identified in the present study. We further demonstrated that, compared to the control, their forefoot produced less force, and their hindfoot produced more force during the push-off phase, suggesting an abnormal force distribution when propelling the body forward.

Though postural asymmetry during walking has been reported among toddlers who were later diagnosed with ASD [Esposito et al., 2011], researchers failed to find gait asymmetry in 5–9 years old children with ASD [Chester & Calhoun, 2012]. Our plantar pressure measurements, instead, revealed that children with ASD walked more asymmetrically than the age-matched controls. Chester and Calhoun (2012) focused on general GVs such as stride length, stance time, and swing time using a motion capture system. However, if people walk straight for a short distance, these kinematic variables shall show high left–right symmetry. In contrast, we evaluated gait asymmetry by analyzing left–right correlations of plantar pressure with kinetic variables reflecting how the whole body interacts with the ground. For instance, the lower limbs can generate distinct force profiles even when their motion remains symmetrical. Our plantar pressure measures indeed were sensitive to detect the increased asymmetry in gait among children with ASD. One caveat is that our participants were older than toddlers in the study of Esposito et al. (2011) but younger than those in the study of Chester and Calhoun (2012). It is still possible that individuals with ASD walk asymmetrically at a young age but gradually normalize their gait during development. This possibility warrants further investigations.

We also found that children with ASD showed increased step-to-step variance in a variety of GVs. Previous studies have found that their walking is more variable in stride length and stride time [Nayate et al., 2012; Rinehart, Tonge, Iansek, et al., 2006]. Accordingly, we found that the contact duration, a component of stride time, showed an increase in the groups with ASD. We went further to show that the traveling distance of CoP, initial CoP position, and a variety of GVs showed increased variance. These results suggest that children with ASD plant their foot on the ground more variably on a step-by-step basis than their age-matched controls.

Our study identified a significant correlation between gait abnormalities and core autistic symptoms when data from all three groups were pooled together. This correlation was not significant when only the two ASD groups were considered. There is growing evidence that motor deficits are associated with the severity of core autistic symptoms. For instance, impaired performance of skilled gestures has been shown as a strong predictor for the defining features of autism as measured by Autism Diagnosis Observation Schedule [Dziuk et al., 2007]. It has been proposed that motor deficits contribute to the development of autism symptoms during early development [for a review, see Cook, 2016]. As early as in infancy, individuals later diagnosed with autism exhibit various motor abnormalities [Esposito et al., 2011; Teitelbaum et al., 1998]. Previous studies on TD children have revealed that poor coordination and slowed movements are associated with poor social participation and increased anxiety during playtime in preschool and kindergarten [Bar-Haim & Bart, 2006; Piek, Bradbury, Elsley, & Tate, 2008]. This has led people to suggest that shared experiences during the playtime are important for building friendships and social connections during typical development [Bhat, Landa, & Galloway, 2011]. Similarly, researchers have found that children with developmental coordination disorder had more social problems than TD controls [Dewey, Kaplan, Crawford, & Wilson, 2002]. For example, motor clumsiness is correlated with long-term social impairments among children with cerebral palsy [Whittingham, Fahey, Rawicki, & Boyd, 2010]. It is thus conceivable that motor atypicality among children with ASD may lead to missed opportunities and reduced interactions with their coordinated and agile peers, limit the initiation and maintenance of friendships, and exert an accumulative effect on their social development. We also acknowledge that our findings do not imply a causal link between gait abnormality and social impairment. Though people have implied that motor deficits contribute to the development of social impairments, it is possible that social impairments can also affect motor development. For example, it has been argued that children with more severe autistic symptoms may imitate others' actions less often [Travers et al.,

2013]; this can negatively impact motor development given the importance of imitation and observational learning among children. Additionally, neurophysiological studies have also found that motor functions and social functions share some common neural basis. Cerebellum and basal ganglia, important neural structures for motor control and learning, are also involved in social processing [Fatemi et al., 2012; Scott-Van Zeeland, Dapretto, Ghahremani, Poldrack, & Bookheimer, 2010].

The gait abnormalities revealed by our plantar pressure measurements can be viewed as affected motor coordination among children with ASD. Walking is associated with distributed brain regions, including both cortical and subcortical areas [Hamacher, Herold, Wiegel, Hamacher, & Schega, 2015]. Among the wide range of neural alterations for autism [see a recent review, Hernandez, Rudie, Green, Bookheimer, & Dapretto, 2015], we postulate that the abnormality in basal ganglia and cerebellum contribute the most to gait impairments [Chukoskie, Townsend, & Westerfield, 2013; Rinehart, Tonge, Iansek, et al., 2006; Qiu, Adler, Crocetti, Miller, & Mostofsky, 2010]. General deficits of motor coordination among individuals with ASD have been linked to disrupted frontostriatal pathways and basal ganglia, dysfunctions in the cerebellum and brain stem [Fournier et al., 2010]. The straight walking requires accurate coordination of body segments. Flat-foot contact and large step-to-step variability identified here can be characterized as poor coordination of ankle movements in the chain of lower limb segments. In the neural hierarchy of motor control, the cerebellum and basal ganglia play an essential role in motor coordination [Bostan, Dum, & Strick, 2013; Debaere, Wenderoth, Sunaert, Van Hecke, & Swinnen, 2004; Spanne & Jorntell, 2013]. In fact, individuals with ASD have shown structural differences in cerebellum and basal ganglia [Chukoskie et al., 2013], that is, reduced size of cerebellar hemispheres and vermis subregions [Ecker et al., 2012; Kaufmann et al., 2003], atypical size and shape of basal ganglia [Qiu et al., 2010]. Of note, many other brain regions and networks might contribute to gait deficits. For example, the asymmetrical gait might be associated with alterations in corpus callosum among individuals with ASD [Prigge et al., 2013; Wolff et al., 2015]. Future studies should combine gait analysis and neurophysiological examinations to reveal the neural basis of motor impairments among individuals with ASD.

Automatic classification of infants or children with ASD has been gaining popularity in recent years. Facial expressions [Liu, Li, & Yi, 2016], behavioral observations or brain activities [Crippa et al., 2015; Deshpande, Libero, Sreenivasan, Deshpande, & Kana, 2013; Duda, Kosmicki, & Wall, 2014; Kosmicki, Sochat, Duda, & Wall, 2015; Stahl, Pickles, Elsabbagh, Johnson, & Team, 2012] have been used as features for classification. The gait deficits identified by our study could serve as potential features given that infants and toddlers start to develop

independent walking from an early age. Though the correlation between gait abnormalities and social impairments identified here does not mean causality, we conceive that motor problems such as walking could contribute to the development of core ASD symptoms. Thus, gait problems deserve more attention for clinicians and parents as they may not be merely motor problems during development. In fact, people have suggested that interventions targeting motor skills have the potential to improve the overall development of children with ASD [Bremer et al., 2015; Bremer & Lloyd, 2016; Pan et al., 2017].

Our study can be improved in at least two aspects. First, we had a small sample size for the LFA group. The reason to have two separate ASD groups is to obtain a group of participants with ASD (the HFA group) who had comparable IQ as the control group. In fact, our two groups with ASD did not differ in most gait measures. Though small and unbalanced sample sizes may lead to the failure of detecting their difference, we still obtained decent power for all the GVs, which ranged from 0.798 to 0.997. We think that the LFA group indeed walk similarly as the HFA group since partial correlation analyses also indicated a negligible effect of IQ. Second, our study did not combine plantar pressure measurements with three-dimensional (3D) motion capture to evaluate limb kinematics. We opted to use plantar pressure measurement alone since our aim is to resolve the inconsistent findings of toe walking and gait asymmetry among children with ASD. In the future, 3D kinematical measurements, particularly important for quantifying upper body motion, can complement the foot pressure measurement, particularly important for quantifying lower-limb kinetics, to evaluate gait deficits among children with ASD comprehensively.

Acknowledgments

The authors are grateful to the staff in Qingdao Elim School and Qingdao Shangwuting kindergarten, especially Ms. Wenyan Nie and Mr. Gong Wang, and children and parents who participated in our study. This work was supported by the National Natural Science Foundation of China (31671168, 31622029, 61533001, 31871116).

References

- Accardo, P., & Whitman, B. (1989). A marker for language disorders: In the developmentally disabled. *Clinical Pediatrics*, 28, 347–350. <https://doi.org/10.1177/000992288902800802>
- American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders* (5th ed.). Washington, DC: Author.
- Auyeung, B., Baron-Cohen, S., Wheelwright, S., & Allison, C. (2008). The Autism Spectrum Quotient: Children's Version (AQ-Child). *Journal of Autism and Developmental Disorders*, 38, 1230–1240. <https://doi.org/10.1007/s10803-007-0504-z>

- Bar-Haim, Y., & Bart, O. (2006). Motor function and social participation in kindergarten children. *Social Development*, 15, 296–310. <https://doi.org/10.1046/j.1467-9507.2006.00342.x>
- Barrow, W. J., Jaworski, M., & Accardo, P. J. (2011). Persistent toe walking in autism. *Journal of Child Neurology*, 26, 619–621. <https://doi.org/10.1177/0883073810385344>
- Bhat, A. N., Landa, R. J., & Galloway, J. C. (2011). Current perspectives on motor functioning in infants, children, and adults with autism spectrum disorders. *Physical Therapy*, 91, 1116–1129. <https://doi.org/10.1016/j.neubiorev.2013.12.001>
- Bostan, A. C., Dum, R. P., & Strick, P. L. (2013). Cerebellar networks with the cerebral cortex and basal ganglia. *Trends in Cognitive Sciences*, 17, 241–254. <https://doi.org/10.1016/j.tics.2013.03.003>
- Bremer, E., Balogh, R., & Lloyd, M. (2015). Effectiveness of a fundamental motor skill intervention for 4-year-old children with autism spectrum disorder: A pilot study. *Autism*, 19, 980–991. <https://doi.org/10.1177/1362361314557548>
- 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, 66–88. <https://doi.org/10.1123/APAQ.2015-0009>
- Cardinale, R. C., Shih, P., Fishman, I., Ford, L. M., & Muller, R. A. (2013). Pervasive rightward asymmetry shifts of functional networks in autism spectrum disorder. *JAMA Psychiatry*, 70, 975–982. <https://doi.org/10.1001/jamapsychiatry.2013.382>
- Cavanagh, P. R., Morag, E., Boulton, A. J. M., Young, M. J., Deffner, K. T., & Pammer, S. E. (1997). The relationship of static foot structure to dynamic foot function. *Journal of Biomechanics*, 30, 243–250. [https://doi.org/10.1016/S0021-9290\(96\)00136-4](https://doi.org/10.1016/S0021-9290(96)00136-4)
- Chester, V. L., & Calhoun, M. (2012). Gait symmetry in children with autism. *Autism Research and Treatment*, 2012, 576478. <https://doi.org/10.1155/2012/576478>
- Chukoskie, L., Townsend, J., & Westerfield, M. (2013). Motor skill in autism spectrum disorders: A subcortical view. *International Review of Neurobiology*, 113, 207–249. <https://doi.org/10.1016/B978-0-12-418700-9.00007-1>
- Constantino, J. N., & Gruber, C. P. (2002). The social responsiveness scale. Los Angeles, CA: Western Psychological Services.
- Cook, J. (2016). From movement kinematics to social cognition: The case of autism. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, 371, 20150372. <https://doi.org/10.1098/rstb.2015.0372>
- Cook, J. L., Blakemore, S. J., & Press, C. (2013). Atypical basic movement kinematics in autism spectrum conditions. *Brain*, 136, 2816–2824. doi.org: <https://doi.org/10.1093/brain/awt208>
- 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. <https://doi.org/10.1007/s10803-015-2379-8>
- Debaere, F., Wenderoth, N., Sunaert, S., Van Hecke, P., & Swinnen, S. P. (2004). Cerebellar and premotor function in bimanual coordination: Parametric neural responses to spatio-temporal complexity and cycling frequency. *NeuroImage*, 21, 1416–1427. <https://doi.org/10.1016/j.neuroimage.2003.12.011>
- Deshpande, G., Libero, L. E., Sreenivasan, K. R., Deshpande, H. D., & Kana, R. K. (2013). Identification of neural connectivity signatures of autism using machine learning. *Frontiers in Human Neuroscience*, 7, 670. <https://doi.org/10.3389/fnhum.2013.00670>
- Dewey, D., Kaplan, B. J., Crawford, S. G., & Wilson, B. N. (2002). Developmental coordination disorder: Associated problems in attention, learning, and psychosocial adjustment. *Human Movement Science*, 21, 905–918. [https://doi.org/10.1016/S0167-9457\(02\)00163-X](https://doi.org/10.1016/S0167-9457(02)00163-X)
- 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, 853–861. <https://doi.org/10.1007/s10803-015-2621-4>
- Dowd, A. M., McGinley, J. L., Taffe, J. R., & Rinehart, N. J. (2012). Do planning and visual integration difficulties underpin motor dysfunction in autism? A kinematic study of young children with autism. *Journal of Autism and Developmental Disorders*, 42, 1539–1548. <https://doi.org/10.1007/s10803-011-1385-8>
- Duda, M., Kosmicki, J. A., & Wall, D. P. (2014). Testing the accuracy of an observation-based classifier for rapid detection of autism risk. *Translational Psychiatry*, 4, e424. <https://doi.org/10.1038/tp.2014.65>
- Dziuk, M. A., Larson, J. G., Apostu, A., Mahone, E. M., Denckla, M. B., & Mostofsky, S. H. (2007). Dyspraxia in autism: Association with motor, social, and communicative deficits. *Developmental Medicine & Child Neurology*, 49, 734–739. doi.org: <https://doi.org/10.1111/j.1469-8749.2007.00734.x>
- Ecker, C., Suckling, J., Deoni, S. C., Lombardo, M. V., Bullmore, E. T., Baron-Cohen, S., ... Williams, S. C. (2012). Brain anatomy and its relationship to behavior in adults with autism spectrum disorder: A multicenter magnetic resonance imaging study. *Archives of General Psychiatry*, 69, 195–209. <https://doi.org/10.1001/archgenpsychiatry.2011.1251>
- 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. doi.org: <https://doi.org/10.2466/pms.106.1.259-269>
- Esposito, G., Venuti, P., Apicella, F., & Muratori, F. (2011). Analysis of unsupported gait in toddlers with autism. *Brain Development*, 33, 367–373. <https://doi.org/10.1016/j.braindev.2010.07.006>
- Esposito, G., Venuti, P., Maestro, S., & Muratori, F. (2009). An exploration of symmetry in early autism spectrum disorders: A of lying. *Brain Development*, 31(2), 131–138. <https://doi.org/10.1016/j.braindev.2008.04.005>
- Fatemi, S. H., Aldinger, K. A., Ashwood, P., Bauman, M. L., Blaha, C. D., Blatt, G. J., ... Welsh, J. P. (2012). Consensus paper: Pathological role of the cerebellum in autism. *Cerebellum*, 11(3), 777–807. <https://doi.org/10.1007/s12311-012-0355-9>
- Flanagan, J. E., Landa, R., Bhat, A., & Bauman, M. (2012). Head lag in infants at risk for autism: A preliminary study. *The American Journal of Occupational Therapy*, 66(5), 577–585. <https://doi.org/10.5014/ajot.2012.004192>
- Fournier, K. A., Hass, C. J., Naik, S. K., Lodha, N., & Cauraugh, J. H. (2010). Motor coordination in autism

- spectrum disorders: A synthesis and meta-analysis. *Journal of Autism and Developmental Disorders*, 40, 1227–1240. <https://doi.org/10.1007/s10803-010-0981-3>
- Fuentes, C. T., Mostofsky, S. H., & Bastian, A. J. (2009). Children with autism show specific handwriting impairments. *Neurology*, 73, 1532–1537. doi.org: <https://doi.org/10.1212/WNL.0b013e3181c0d48c>
- Gatev, P., Homas, S., Kepple, T., & Hallett, M. (1999). Feedforward ankle strategy of balance during quiet stance in adults. *The Journal of Physiology*, 514(3), 915–928. <https://doi.org/10.1111/j.1469-7793.1999.915ad.x>
- Hallemans, A., D'Août, K., De Clercq, D., & Aerts, P. (2003). Pressure distribution patterns under the feet of new walkers: The first two months of independent walking. *Foot & Ankle International*, 24, 444–453. doi.org: <https://doi.org/10.1177/107110070302400513>
- Hamacher, D., Herold, F., Wiegel, P., Hamacher, D., & Schega, L. (2015). Brain activity during walking: A systematic review. *Neuroscience and Biobehavioral Reviews*, 57, 310–327. <https://doi.org/10.1016/j.neubiorev.2015.08.002>
- Hayafune, N., Hayafune, Y., & Jacob, H. A. C. (1999). Pressure and force distribution characteristics under the normal foot during the push-off phase in gait. *The Foot*, 9, 88–92. <https://doi.org/10.1054/foot.1999.0518>
- Hennig, E. M., & Rosenbaum, D. (1991). Pressure distribution patterns under the feet of children in comparison with adults. *Foot & Ankle International*, 11, 306–311. <https://doi.org/10.1177/107110079101100507>
- Hennig, E. M., Staats, A., & Rosenbaum, D. (1994). Plantar pressure distribution patterns of young school children in comparison to adults. *Foot & Ankle International*, 15, 35–40. <https://doi.org/10.1177/107110079401500107>
- Hernandez, L. M., Rudie, J. D., Green, S. A., Bookheimer, S., & Dapretto, M. (2015). Neural signatures of autism spectrum disorders: Insights into brain network dynamics. *Neuropsychopharmacology*, 40, 171–189. <https://doi.org/10.1038/npp.2014.172>
- Jansiewicz, E. M., Goldberg, M. C., Newschaffer, C. J., Denckla, M. B., Landa, R., & Mostofsky, S. H. (2006). Motor signs distinguish children with high functioning autism and Asperger's syndrome from controls. *Journal of Autism and Developmental Disorders*, 36, 613–621. <https://doi.org/10.1007/s10803-006-0109-y>
- Kaufmann, W. E., Cooper, K. L., Mostofsky, S. H., Capone, G. T., Kates, W. R., Newschaffer, C. J., ... Lanham, D. C. (2003). Specificity of cerebellar vermian abnormalities in autism: A quantitative magnetic resonance imaging study. *Journal of Child Neurology*, 18, 463–470. <https://doi.org/10.1177/08830738030180070501>
- 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*, 21, 481–492. <https://doi.org/10.1177/1362361316650611>
- Kosmicki, J. A., Sochat, V., Duda, M., & Wall, D. P. (2015). Searching for a minimal set of behaviors for autism detection through feature selection-based machine learning. *Translational Psychiatry*, 5, e514. <https://doi.org/10.1038/tp.2015.7>
- Liu, W., Li, M., & Yi, L. (2016). Identifying children with autism spectrum disorder based on their face processing abnormality: A machine learning framework. *Autism Research*, 9(8), 888–898. <https://doi.org/10.1002/aur.1615>
- Memari, A. H., Ghanouni, P., Shayestehfar, M., & Ghaheeri, B. (2014). Postural control impairments in individuals with autism spectrum disorder: A critical review of current literature. *Asian Journal of Sports Medicine*, 5, e22963. <https://doi.org/10.5812/asjms.22963>
- Ming, X., Brimacombe, M., & Wagner, G. C. (2007). Prevalence of motor impairment in autism spectrum disorders. *Brain Development*, 29, 565–570. <https://doi.org/10.1016/j.braindev.2007.03.002>
- Minschew, N. J., Sung, K., Jones, B. L., & Furman, J. M. (2004). Underdevelopment of the postural control system in autism. *Neurology*, 63, 2056–2061. <https://doi.org/10.1212/01.WNL.0000145771.98657.62>
- Nayate, A., Tonge, B. J., Bradshaw, J. L., McGinley, J. L., Iansek, R., & Rinehart, N. J. (2012). Differentiation of high-functioning autism and Asperger's disorder based on neuromotor behaviour. *Journal of Autism and Developmental Disorders*, 42, 707–717. <https://doi.org/10.1007/s10803-011-1299-5>
- 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*, 15, 263–283. <https://doi.org/10.1177/1362361309356929>
- Pan, C. Y., Chu, C. H., Tsai, C. L., Sung, M. C., Huang, C. Y., & Ma, W. Y. (2017). The impacts of physical activity intervention on physical and cognitive outcomes in children with autism spectrum disorder. *Autism*, 21(2), 190–202. <https://doi.org/10.1177/1362361316633562>
- Piek, J. P., Bradbury, G. S., Elsley, S. C., & Tate, L. (2008). Motor coordination and social-emotional behaviour in preschool-aged children. *International Journal of Disability, Development and Education*, 55, 143–151. <https://doi.org/10.1080/10349120802033592>
- Prigge, M. B., Lange, N., Bigler, E. D., Merkley, T. L., Neeley, E. S., Abildskov, T. J., ... Lainhart, J. E. (2013). Corpus callosum area in children and adults with autism. *Research in Autism Spectrum Disorder*, 7, 221–234. <https://doi.org/10.1016/j.rasd.2012.09.007>
- Qiu, A., Adler, M., Crocetti, D., Miller, M. I., & Mostofsky, S. H. (2010). Basal ganglia shapes predict social, communication, and motor dysfunctions in boys with autism spectrum disorder. *Journal of the American Academy of Child & Adolescent Psychiatry*, 49, 539–551. <https://doi.org/10.1016/j.jaac.2010.02.012>
- Radonovich, K. J., Fournier, K. A., & Hass, C. J. (2013). Relationship between postural control and restricted, repetitive behaviors in autism spectrum disorders. *Frontiers in Integrative Neuroscience*, 7, 28. <https://doi.org/10.3389/fnint.2013.00028>
- Rinehart, N. J., Bellgrove, M. A., Tonge, B. J., Brereton, A. V., Howells-Rankin, D., & Bradshaw, J. L. (2006). An examination of movement kinematics in young people with high-functioning autism and Asperger's disorder: Further evidence for a motor planning deficit. *Journal of Autism and Developmental Disorders*, 36, 757–767. <https://doi.org/10.1007/s10803-006-0118-x>
- Rinehart, N. J., Tonge, B. J., Iansek, R., McGinley, J., Brereton, A. V., Enticott, P. G., & Bradshaw, J. L. (2006). Gait

- function in newly diagnosed children with autism: Cerebellar and basal ganglia related motor disorder. *Developmental Medicine and Child Neurology*, 48, 819–824. <https://doi.org/10.1017/S0012162206001769>
- Scott-Van Zeeland, A. A., Dapretto, M., Ghahremani, D. G., Poldrack, R. A., & Bookheimer, S. Y. (2010). Reward processing in autism. *Autism Research*, 3, 53–67. <https://doi.org/10.1002/aur.122>
- Shetreat-Klein, M., Shinnar, S., & Rapin, I. (2014). Abnormalities of joint mobility and gait in children with autism spectrum disorders. *Brain Development*, 36, 91–96. <https://doi.org/10.1016/j.braindev.2012.02.005>
- Spanne, A., & Jorntell, H. (2013). Processing of multi-dimensional sensorimotor information in the spinal and cerebellar neuronal circuitry: A new hypothesis. *PLoS Computational Biology*, 9, e1002979. <https://doi.org/10.1371/journal.pcbi.1002979>
- Stahl, D., Pickles, A., Elsabbagh, M., Johnson, M. H., & BASIS Team. (2012). Novel machine learning methods for ERP analysis: A validation from research on infants at risk for autism. *Developmental Neuropsychology*, 37(3), 274–298. <https://doi.org/10.1080/87565641.2011.650808>
- Suzuki, Y., Nomura, T., Casadio, M., & Morasso, P. (2012). Intermittent control with ankle, hip, and mixed strategies during quiet standing: A theoretical proposal based on a double inverted pendulum model. *Journal of Theoretical Biology*, 310, 55–79. <https://doi.org/10.1016/j.jtbi.2012.06.019>
- Teitelbaum, O., Benton, T., Shah, P. K., Prince, A., Kelly, J. L., & Teitelbaum, P. (2004). Eshkol–Wachman movement notation in diagnosis: The early detection of Asperger's syndrome. *Proceedings of the National Academy of Sciences of the United States of America*, 101, 11909–11914. <https://doi.org/10.1073/pnas.0403919101>
- Teitelbaum, P., Teitelbaum, O., Nye, J., Fryman, J., & Maurer, R. G. (1998). Movement analysis in infancy may be useful for early diagnosis of autism. *Proceedings of the National Academy of Sciences*, 95, 13982–13987. <https://doi.org/10.1073/pnas.0403919101>
- Travers, B. G., Powell, P. S., Klinger, L. G., & Klinger, M. R. (2013). Motor difficulties in autism spectrum disorder: Linking symptom severity and postural stability. *Journal of Autism and Developmental Disorders*, 43, 1568–1583. <https://doi.org/10.1007/s10803-012-1702-x>
- Uljarevic, M., Hedley, D., Alvares, G. A., Varcin, K. J., & Whitehouse, A. J. O. (2017). Relationship between early motor milestones and severity of restricted and repetitive behaviors in children and adolescents with autism spectrum disorder. *Autism Research*, 10, 1163–1168. <https://doi.org/10.1002/aur.1763>
- Valagussa, G., Trentin, L., Balatti, V., & Grossi, E. (2017). Assessment of presentation patterns, clinical severity, and sensorial mechanism of tip-toe behavior in severe ASD subjects with intellectual disability: A cohort observational study. *Autism Research*, 10, 1547–1557. <https://doi.org/10.1002/aur.1796>
- Valagussa, G., Trentin, L., Signori, A., & Grossi, E. (2018). Toe walking assessment in autism spectrum disorder subjects: A systematic review. *Autism Research*, 11, 1404–1415. <https://doi.org/10.1002/aur.2009>
- Vanvuchelen, M., Roeyers, H., & De Weerd, W. (2007). Nature of motor imitation problems in school-aged boys with autism: A motor or a cognitive problem? *Autism*, 11, 225–240. <https://doi.org/10.1177/1362361307076846>
- Vercher, J. L., & Gauthier, G. M. (1988). Cerebellar involvement in the coordination control of the oculo-manual tracking system: Effects of cerebellar dentate nucleus lesion. *Experimental Brain Research*, 73(1), 155–166. <https://doi.org/10.1007/bf00279669>
- Vilensky, J. A., Damasio, A. R., & Maurer, R. G. (1981). Gait disturbances in patients with autistic behavior: A preliminary study. *Archives of Neurology*, 38, 646–649. <https://doi.org/10.1001/archneur.1981.00510100074013>
- Wechsler, D. (2014). Wechsler Intelligence Scale for Preschool and Primary Children-Fourth CN Edition. Hong Kong, China: King-May Company.
- Wen, J., Ding, Q., Yu, Z., Sun, W., Wang, Q., & Wei, K. (2012). Adaptive changes of foot pressure in hallux valgus patients. *Gait & Posture*, 36, 344–349. <https://doi.org/10.1016/j.gaitpost.2012.03.030>
- Whittingham, K., Fahey, M., Rawicki, B., & Boyd, R. (2010). The relationship between motor abilities and early social development in a preschool cohort of children with cerebral palsy. *Research in Developmental Disabilities*, 31, 1346–1351. <https://doi.org/10.1016/j.ridd.2010.07.006>
- Wolff, J. J., Gerig, G., Lewis, J. D., Soda, T., Styner, M. A., Vachet, C., ... Network, I. (2015). Altered corpus callosum morphology associated with autism over the first 2 years of life. *Brain*, 138, 2046–2058. <https://doi.org/10.1093/brain/awv118>

Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Table S1. Partial Correlation Between Gait Variables and Scales of AQ and SRS.