



Gait patterns in children with autism spectrum disorder: A systematic review

Aikaterini Ioannidou^{a,*}, Pinelopi Vlotinou^{b,**}, Anna Tsiakiri^c, Nikolaos Aggelousis^d, Georgios Labiris^e, Aspasia Serdari^a

^a Department of Psychiatry and Child Psychiatry, Democritus University of Thrace, University Hospital of Alexandroupolis, Thrace, Greece

^b Department of Occupational Therapy, University of West Attica, 12243, Athens, Greece

^c Neurology Department, School of Medicine, Democritus University of Thrace, 68100, Alexandroupolis, Greece

^d Department of Physical Education and Sport Science, Democritus University of Thrace, 69100, Komotini, Greece

^e Ophthalmology Department, University Hospital of Alexandroupolis, Dragana, 68100, Alexandroupolis, Greece

ARTICLE INFO

Keywords:

Gait analysis
Motor coordination
Autism spectrum disorder
Paediatric population

ABSTRACT

Background: Differences in walking patterns have been observed by clinicians working with children with Autism Spectrum Disorders (ASD). Different gait parameters have been studied and emerged through the recent years. The purpose of this review is to summarize the gait patterns that have been studied during the last decade in children with ASD.

Methods: Pubmed, Scopus, PsycINFO, and Google Scholar databases were screened for publications examining differences in gait patterns in children with ASD. Included articles were written in English, published during the last decade (2013–2024), regarding childhood age of participants and examining gait patterns in children with ASD. Initial database search retrieved 289 studies and 17 were included in this review. Gait parameters, including spatiotemporal parameters (stride length, stride width, and cadence), joint mobility parameters (knee flexion, ankle flexion, and dorsiflexion), stability, asymmetry, and toe-walking are the main parameters which were further investigated.

Results: Study selection process, study and participants' characteristics, diagnostic scales, scales for mobility assessment and methods utilized for gait assessment were described for each study. Gait parameters are affected in children with ASD. Specifically, greater stride width, increased gait variability and decreased stability during walking are the most consistent findings across the studies. For many variables, such as stride length, cadence, symmetry, and joint mobility parameters, the results are still inconclusive and further research is needed.

Conclusion: Existing research is limited in its ability to draw firm conclusions. Small sample size, methodological differences and group deviation consist the main limitations regarding the generalizability of the results. Therefore, scientific interest should focus more on mobility variations in children with ASD in the future.

1. Introduction

Autism spectrum disorder (ASD) is a complex neurodevelopmental disorder characterized by persistent deficits in social communication and interaction, as well as a range of restricted, repetitive behaviors and interests that are notably atypical or excessive given the individual's age

and sociocultural context according to International Classification of Diseases-11th edition (ICD-11).¹ The prevalence of ASD has markedly increased over the past two decades. Data from the Centers for Disease Control and Prevention (CDC)² indicate that the prevalence of ASD was 1 in 150 children in the year 2000, rising to approximately 1 in 36 children in recent estimates.

* Corresponding author.

** Corresponding author.

E-mail address: katerioan@yahoo.gr (A. Ioannidou).

Peer review under the responsibility of Editorial Board of Sports Medicine and Health Science

<https://doi.org/10.1016/j.smhs.2025.11.002>

Received 1 November 2024; Received in revised form 28 October 2025; Accepted 28 November 2025

Available online xxxx

2666-3376/© 2025 Chengdu Sport University. Publishing services by Elsevier B.V. on behalf of KeAi Communications Co. Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

ASD	Autism Spectrum Disorder
ICD	International Classification of Diseases
CDC	Centers for Disease Control and Prevention
DSM	Diagnostic and Statistical Manual
WHO	World Health Organization
NOS	Newcastle-Ottawa Scale
TD	Typically Developing
ADOS	Autism Diagnostic Observation Schedule
AQ-Child	Autism Spectrum Quotient: Child's Version
ATEC	Autism Treatment Evaluation Checklist
CARS	Childhood Autism Rating Scale
ADI-R	Autism Diagnostic Interview-Revised
MABC	Movement Assessment Battery for Children
DGDQ	Developmental Coordination Disorder Questionnaire
CAREN	Computer Assisted Rehabilitation Network
IMUs	Inertial Measurement Units
COP	Center Of Pressure
GRF	Ground Reaction Forces
LFA	Low-Functioning Autism
HFA	High-Functioning Autism
VGRF	Vertical Ground Reaction Forces
TTB	Tip-Toe Behavior
CV	Coefficient of Variations
FSIQ	Full-Scale Intelligence Quotient
SRS	Social Responsiveness Scale
WPPSI-IV	Wechsler Preschool and Primary Scale of Intelligence-Forth Edition
SCQ	Social Communication Questionnaire
WISC	Wechsler Intelligence Scale for Children
WASI	Wechsler Abbreviated Scales of Intelligence
AQ	Autism Quotient checklist
CRP	Continuous Relative Phase
vCRP	Coordination Variability
MVIC	Maximal Voluntary Isometric Contractions

Motor impairments, including repetitive and stereotyped movements, such as body rocking or unusual hand postures are significant but often underemphasized aspects of ASD.¹ Kanner described the gait of children with ASD as “clumsy” and “uncoordinated” in 1943, highlighting the long-standing recognition of motor issues.^{3,4} These motor deficiencies, may consist the first identifiable impairments observed in toddlers and infants who may develop ASD diagnosis,⁵ including delays in motor milestones (sitting, walking independently).⁶ These motor delays are considered important as they could impact on spatial perception, exploration of the environment, and interaction with caregivers during the first months of life.⁷ Despite the primary emphasis on social and communication deficits, motor impairments are highly prevalent, affecting up to 80% of individuals with ASD,^{8–11} and have been proposed as potential core features although a consensus has not yet been reached.^{12,13}

Motor skills deficits are also crucial for understanding the pathophysiology of ASD and could depict the generalized neuromotor dysfunction as well as the continuous interaction between the environment and the developing brain.^{7,14–16} It is further hypothesized that they contribute substantially to the characteristic social impairments of ASD^{5,9,17} and negatively impact daily functioning and quality of life.^{6,8,11,13,18,19} They can lead to decreased participation in physical activities, further exacerbating motor difficulties, thus creating a detrimental feedback loop.¹⁷ Reduced engagement in activities can subsequently result in social isolation, feelings of alienation, anxiety, and depression thus affecting the psychosocial development and mental health of children with ASD.^{6,11,17}

Recent years have seen a surge in research focusing on motor skills in children with ASD.^{20,21} Gait analysis, a fundamental component of motor skills assessment, is particularly relevant due to its essential role in mobility and independence.^{13,22} Abnormal gait patterns, especially toe walking, are frequently documented in children with ASD.²³ Clinical observation suggests variability in gait in autistic children, which is vital for humans in order to adjust to environmental changes (different surfaces or objects). Though, too high or too low variability may consist a

serious obstacle in this environmental adaptation.⁴ Gait assessment in ASD involves analysing various parameters such as gait abnormalities,^{5,6} postural control,^{5,24} stability,¹³ asymmetry,^{20,25} joint mobility,^{25,26} and toe-walking.^{11,23}

In light of the aforementioned reasons, it is of the utmost importance to undertake further study of motor performance, which is currently still limited.²⁷ Improved understanding of motor impairments in ASD can inform the development of more effective treatment and intervention programs.^{4,6,11,13,17,25,28} In addition, they are considered essential for the inclusion in the key diagnostic criteria¹⁶ contributing to early detection and intervention.¹⁷

As has been previously observed, children diagnosed with ASD have been shown to exhibit pervasive motor coordination deficits, altered spatiotemporal gait parameters (e.g. increased step width, variable stride length) and impairments in postural control when compared to typically developing peers.^{8,28} However, the extant reviews have either covered motor skills more broadly or included only a limited set of gait studies. In contrast to earlier reviews that synthesised a larger body of heterogeneous studies, the present work focuses on a smaller but more recent set of investigations, thereby providing an updated and targeted overview of gait patterns in children with ASD.

This systematic review aims to synthesize the findings of recent research on gait patterns in children with ASD over the past decade, providing a comprehensive overview of the current state of knowledge and identifying avenues for future investigation.

2. Methods

2.1. Protocol registration

The current review was conducted and reported with the guidance of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) statement.²⁹ The present study is prospectively registered with PROSPERO (PROSPERO registration number: CRD42024583687).

2.2. Materials

The literature search was conducted using the PubMed, Scopus, PsychInfo and Google Scholar electronic databases. The search terms employed were “autism”, “gait patterns” and “children”. The keywords were combined by applying Boolean operators across all databases. For instance, the PubMed strategy string was (autism OR “autism spectrum disorder” OR ASD) AND (gait OR “gait patterns”) AND (child OR children). Additionally, the diagnostic criteria for Autism Spectrum Disorder (ASD) were referenced using the electronic version of the 11th edition of the International Classification of Diseases (ICD-11) provided by the World Health Organization (WHO).¹ Although MeSH terms are recommended for systematic reviews, we chose not to use them in this study to avoid excluding recent publications (2023–2024) that have not yet been indexed. While this approach may appear less complex than traditional MeSH-based strategies, it was deliberately chosen to balance comprehensiveness with sensitivity to newly published articles. To further enhance transparency, a comprehensive record of the precise keyword combinations utilized across various databases has been documented and made accessible upon request.

2.3. Inclusion and exclusion criteria

Original full-text articles in English were included. Articles published between January 2013 and April 2024 and published in a peer-reviewed journal were included. Studies were included in the review if they involved children aged 4–12 years, even if the overall sample also contained younger or older participants. This age criterion was established as childhood is conventionally considered to span from age 4 to age 12, and this study focuses on investigating gait characteristics

during this developmental period. If the sample was divided into age groups, only data from the 4–12-year-old group were considered for gait parameter analysis, while data from younger or older age groups were excluded. Articles included studied gait parameters in children with ASD.

Articles published in a language other than English were excluded. Studies that did not include participants between 4 and 12 years old were excluded. Studies searching for gait patterns after therapeutic intervention, without reference to specific gait parameters or studies comparing methodological issues regarding gait measurements were also excluded. In addition, studies focusing exclusively on postural control during quiet stance were excluded, as the present review aimed specifically to synthesize gait parameters. Finally, studies that concerned any other neurodevelopmental disorder or syndrome were excluded.

To increase the clarity of our eligibility framework, we structured our inclusion and exclusion criteria according to the PICOS approach (Table 1). This framework allowed a systematic and transparent evaluation of studies relevant to the review question, ensuring consistency during screening and data extraction.

2.4. Data extraction

The PRISMA guidelines for systematic review were followed to search literature, select studies and extract information (Fig. 1). Screening of titles, abstracts and full-text articles was undertaken by two independent reviewers, VP & IA who independently screened titles and abstracts, and subsequently assessed full texts against predetermined inclusion criteria. Discrepancies were addressed through deliberation, and the involvement of a third reviewer was deemed necessary to resolve any outstanding issues.

A data extraction protocol was meticulously designed to encompass a comprehensive array of information. This protocol was implemented through a piloted form, which systematically captured pertinent details such as the author's credentials, the year of publication, the sample size, and the characteristics of the participants, including the severity of autism spectrum disorder (ASD), the presence of intellectual disability (ID), and comorbidities. Additionally, the study design, the protocol for gait assessment, the instrumentation utilized, the measured parameters, and the primary outcomes were meticulously documented. The process of data extraction was executed by a single reviewer and subsequently verified by a second reviewer.

After the screening process, a total of 17 studies were identified that met the above inclusion criteria. Detailed information regarding methods, scales, main results, and limitations of each study is described in Table 2.

2.5. Risk of bias assessment

Two independent assessors, I.A. and T. A., assessed the risk of bias and quality of evidence for each of the included study separately. Quality Assessment Tool for Quantitative Studies, Newcastle-Ottawa

Scale (NOS) for case control studies,³⁸ was used to analyse the quality of evidence and the risk of bias for the included studies. The NOS was developed to assess the quality of nonrandomized studies and uses a “nine-star system” in which a study is assessed for the least risk of bias in three components: the selection of study groups (four points); the comparability of groups (two points); and the ascertainment of exposure and outcomes (three points). Thus, the maximum for each study is nine, with studies having more than six points being identified as representing at low risk of bias.³⁹ The rating system indicates that studies that score 0–2 have poor quality; 3–5 fair quality; 6–9 good/high quality.⁴⁰ Two investigators ranked the studies according to the NOS criteria. The two investigators agreed on the ranking of the studies. In case of disagreement, a third investigator would be asked to re-rank the studies to resolve the discrepancy. Two studies were categorized as poor quality, 7 studies as fair quality and 8 studies as high quality (Table 3). The rationale behind retaining the low-quality studies was to ensure the comprehensive collection of research data, given the limited availability of studies in this field. Furthermore, it was deemed essential to include these findings, as they were deemed to be of significant importance and should not be excluded from the analysis.

The data were only descriptively analysed, while the high level of heterogeneity among the studies did not allow holding statistical analysis or meta-analysis.

3. Results

3.1. Study selection process

A total of 289 studies were initially identified through the search. After removing duplicates, 223 articles remained for screening based on the predetermined inclusion and exclusion criteria. Of these, 45 articles were deemed eligible for data extraction and quality assessment, as illustrated in Fig. 1. The most common reasons for exclusion were studies focusing on age groups outside of childhood (toddlers or adolescents), investigations of disorders or syndromes other than ASD, and the absence of gait parameter analysis. Ultimately, 32 studies were thoroughly evaluated using the inclusion and exclusion criteria and 17 studies met the criteria for inclusion in this review.

3.2. Study characteristics

In the analysis of each selected article, several critical factors were systematically considered. These included:

“Age and Diagnosis of Participants”: The age range and diagnostic criteria for ASD among the participants were scrutinized to ensure consistency and relevance to the study objectives. Measures and Scales that were used: The various “assessment tools and scales employed” in each study were documented, providing insight into the reliability and validity of the measures used. “Methods for measuring Gait Parameters”: The “methodologies” used to evaluate gait parameters were examined. This included motion capture systems, force plates, or other biomechanical assessment tools that were utilized. “Gait parameters”: The

Table 1
PICOS framework.

PICOS	
Participants	Children aged 4–12 years diagnosed with ASD; studies including wider age ranges were considered only if data for the 4–12 range were extractable.
Intervention/ exposure	Natural gait assessment or in loaded conditions in children with ASD, without therapeutic interventions (i.e., observational studies assessing gait patterns).
Comparators	Studies with or without a control group; if present, controls were TD children. Studies with other neurodevelopmental disorders as comparators were excluded.
Outcomes	Quantitative analysis of gait parameters such as stride length, step width, cadence, postural control, joint mobility, toe-walking, asymmetry, COP, and gait variability.
Study design	Original, peer-reviewed quantitative studies (e.g., observational, case-control, cross-sectional) published between 2013 and April 2024 in English. Reviews, case reports, or intervention-only studies were excluded.

Abbreviations: ASD = Autism Spectrum Disorder, TD = Typically Developing, COP = Center Of Pressure.

Table 2
Description of manuscripts included.

Author	Manuscript	Year of publication, place	Participants	groups	Scales used	Purpose	Methodology	Procedure	Results	Limitations
Valagussa G., Purpura G., Balatti V., Trentin L., Signori A., Grossi E. ¹¹	Quantitative assessment of tip-toe behavior in individuals with autism spectrum disorder and intellectual disability: A cross-sectional study	2024	50 ASD participants, 4–26 years old (mean age = 13.35)	No group deviation	ADOS-2 (Autism Diagnostic Observation Schedule)	Propose a quantitative approach to TTB (Tip-toe behavior), assess feasibility, analyse subgroups	Observational/report-based, video-based coding	Structured interviews, video-recording during static and dynamic conditions	TTB3 subgroup had higher TTB time - higher ADOS scores in TTB group ($p = 0.006$)	- Requires two operators - video subjectivity, severity of ASD diagnosis affects generalizability
Gong L., Liu Y., Yi L., Fang J., Yang Y., and Wei K. ³⁰	Abnormal Gait Patterns in Autism Spectrum Disorder and Their Correlations with Social Impairments	2020	86 children 4–6 years old	3 groups: ASD high/low IQ & control	- Full-Scale Intelligence Quotient (FSIQ) Autism Spectrum Quotient: Children's Version (AQ-Child) Social Responsiveness Scale (SRS) Wechsler Preschool and Primary Scale of Intelligence-Forth Edition-IV (WPPSI-IV)	Resolve inconsistencies in gait asymmetry, correlate gait with social impairments	Plantar pressure measurements	6 m barefoot walking on embedded pressure mat	ASD group had flat-footed pattern - more asymmetry in ASD group - longer forefoot contact ($p < 0.001$)	- Small low-functioning group - no 3D motion capture
Olivas N. A., Kendall R. M., Parada A., Manning R., Eggleston D. J. ²⁶	Children with autism display altered ankle strategies when changing speed during over-ground gait	2022	14 children with ASD (8–17 years old)	-no group deviation	-no scales mentioned	Examine kinematics at different speeds	10-camera 3D motion capture	36 trials at preferred, fast, and slow speeds	- Altered ankle joint motion - increased knee/hip flexion - reduced dorsiflexion	No ASD scale, physical activity not checked, growth/development variation
Lim, B., O'Sullivan D., Choi B., Kim M. ³¹	Comparative gait analysis between children with autism and age-matched controls: Analysis with temporal-spatial and foot pressure variables	2016	30 children 8–12 years old	2 groups, 1 ($n = 15$) children with ASD and 1 ($n = 15$) TD control group	- no scales mentioned	Investigate gait via temporal-spatial and foot pressure variables	GAITrite plantar pressure system	Barefoot walking over an 8 m path	Longer gait cycle ($p = 0.042$), stance time ($p = 0.01$), double support time ($p = 0.004$) for ASD group -lower cadence, step/extremity ratio and slower stride velocity for ASD group - wider step width ($p = 0.008$) and later peak pressure times ($p = 0.002$) for ASD children	Cannot relate limb kinematics with plantar pressure

(continued on next page)

SP-
ec-
ifc

Table 2 (continued)

Author	Manuscript	Year of publication, place	Participants	groups	Scales used	Purpose	Methodology	Procedure	Results	Limitations
Biffi E., Costantini C., Ceccarelli S., Cesareo A., Marzocchi G.M., Nobile M., Molteni M. and Crippa A. ²¹	Gait Pattern and Motor Performance During Discrete Gait Perturbation in Children With Autism Spectrum Disorders	2018	31 children 7–12 years old	Two groups: –15 with ASD – 16 TD	- Wechsler Intelligence Scale for Children fourth edition (WISC- IV) - Social Responsiveness Scales (SRS) (parents) - SCQ–Lifetime (parents of TD children) - Movement Assessment Battery for Children 2 (MABC2) - Developmental Coordination Disorder Questionnaire (DCDQ) (parents)	Examine gait perturbation response in ASD	3D motion analysis on treadmill	Walking with split- belt perturbations	- atypical hip flexion ($p = 0.031$) and anterior pelvis displacement ($p = 0.007$) - Reduced ankle GRF, increased hip flexion, wider base of support	Small sample, only high-functioning children
Manicolo O., Brotzmann m., Hagmann- von Arx p., Grob a., Weber p. ⁶	Gait in children with infantile/ atypical autism: Age-dependent decrease in gait variability and associations with motor skills	2018	68 children 4–17 years old	32 children with ASD and 36 controls	MABC	Examine gait variability and motor skills correlations	- GAITRite electronic walkway system	- 10m walking - Gait parameters measured: velocity, stride time, stride length, base of support, gait variability	- ASD group had higher gait variability, wider base of support ($p < 0.001$) - no differences for velocity, stride time, or stride length - older walking age in ASD children (16.4 months vs 13.3)	- GAITRite does not take individual walking patterns into consideration - most children were not under medication so no possible medication effects were able to be explored
Hasan C. Z. C., Jailani R., Tahir N., Ilias S. ¹³	The analysis of three- dimensional ground reaction forces during gait in children with autism spectrum disorders	2017	40 children 4.3–12.4 years old	2 groups, 1 ($n = 15$) children with ASD and 1 ($n = 25$) Typically Developing (TD) children	-no scales used	Investigate 3D ground reaction forces (GRF) divergence in ASD	Force plates analysis	Barefoot walking on 6.5 m walkway	- Higher maximum braking force of the anterior- posterior GRF in ASD group ($p = 0.029$) - greater instability and inconsistency in ASD children - great anterior- posterior vari- ability and verti- cal GRF patterns	- insufficient quantitative results - small sample size - no examination of the relationship between gait parameters
Eggleston D. J., Landers R. M., Bates T. B. ,	Examination of gait parameters during perturbed over-ground	2018	- 8 children with ASD 7–16 years old	1 group	- no scales mentioned	Examine lower extremity mechanics under	- 10- camera motion capture system (200 Hz; Vicon Motion	- Walking with/ without weighted vest/backpack (15	- no symmetry changes in loaded processes	- ASD previous diagnosed - no control group

(continued on next page)

Table 2 (continued)

Author	Manuscript	Year of publication, place	Participants	groups	Scales used	Purpose	Methodology	Procedure	Results	Limitations
Nagelhout E., Dufek S. J. ³	walking in children with autism spectrum disorder					weighted conditions	Systems, Ltd., Oxford, UK).	trials for each condition.	- vno significant affection in knee or ankle impact	- 15% BM mass may be too much weight - no walking homogeneity regarding wearing shoes - no female participants
Eggleston D. J., Harry R.J., Cereceres A. P., Olivas N. A., Chavez A. E., Boyle B. J., Dufek S. J. ²²	Lesser magnitudes of lower extremity variability during terminal swing characterizes walking patterns in children with autism	2020	- 20 children 5–12 years old	- 2 groups, 1 ($n = 11$) with ASD and 1 ($n = 9$) typically developing children	- no scales used	- Examine gait variability in ASD	- 8-camera three-dimensional motion capture system (120 Hz; Vicon Motion Motion Systems, Ltd., Oxford, UK)	- 12 motion trials during walking on a 9-m path at a self-preferred speed	- different lower extremity vCRP for ASD group in every gait cycle sub-phase ($p \leq 0.05$) - no significant stride length variability - greater stride width variability in ASD group	- small sample size - little developmental and diagnostic details - gait speed not checked
Li Y., Koldenhoven M. R., Liu T., Venut E. C. ²⁵	Age-related gait development in children with autism spectrum disorder	2021	29 children with mild ASD 6–14 years old	3 subgroups based on age, one 6–8 years old, one 9–11 years old and one 12–14 years old	- no scales mentioned	Investigate age-related gait changes	- Inertial measurement units (IMU, Noraxon USA Inc., Scottsdale, AZ, USA) were used to collect kinematic data at a sampling frequency of 100 Hz	- self-preferred-speed walking - ten consecutive steps (i.e., five consecutive strides) for each child were analysed.	- greater ankle dorsiflexion ($p < 0.01$) and knee flexion at heel-strike ($p < 0.01$), reduced energy-efficient walking and restricted arm swing in younger children - ($p < 0.01$) increased ankle dorsiflexion at heel strike and increased ($p < 0.01$) knee flexion angle at heel strike - significantly increased ankle dorsiflexion angle ($p = 0.01$) at toe-off -no symmetry differences	- small sample - group variations could influence walking variables - different types of shoes may affect the results - different physical activity between children
Shetreat-Klein M., Shinnar S., Rapin I. ²³	Abnormalities of joint mobility and gait in children with autism spectrum disorders	2014	76 children 2–10 years old	2 groups, 1 ($n = 38$) with ASD and 1 ($n = 38$) typically developing children	- no scales mentioned	Examine joint mobility and gait abnormalities	- video recording of gait	- maximum active joint mobility measured - recording while walking and running without shoes on a hallway	- greater supple joints in ASD group ($p < 0.0001$ – 0.02) - older age of autonomously walking in ASD	- small sample size - short video duration - the reliability of clinical gait scoring is inconsistent

(continued on next page)

Table 2 (continued)

Author	Manuscript	Year of publication, place	Participants	groups	Scales used	Purpose	Methodology	Procedure	Results	Limitations
								in physician's office for 1–2 min	children (mean 1.6 months older) ($p = 0.005$) - more frequently toe-walking in children with ASD ($p = 0.0001$)	- blinding to ASD diagnosis is problematic
Wu X., D. Dickin C. D., Bassette L., Ashton C., Wang H. ³²	Clinical gait analysis in older children with autism spectrum disorder	2024	22 children, 9–17 years old	2 groups, 1 ($n = 11$) with ASD and 1 ($n = 11$) TD control group	- no scales mentioned	Compare gait and knee muscle length in ASD	- 15 camera Vicon system v on an AMTI force-instrumented treadmill	- 22 retro-reflective markers and 6 marker clusters placed on children - 5 min familiarization walking on the treadmill. - maximal voluntary isometric contractions (MVIC) on a Cybex dynamometer	- 6% shorter stride length - 8% greater cadence - no differences in stride width ($p = 0.33$) - 14% greater Antero-Posterior braking GRF - 15% shorter knee extension - reduced peak-off vertical GRF	- sensory impairments not evaluated
Hasan C. Z.C, JailaniR., Tahir N. M., Desa H. M. ³³	Vertical Ground Reaction Force Gait Patterns During Walking in Children with Autism Spectrum Disorders	2018	60 participants 4–12 years old	2 groups, 1 ($n = 30$) ASD group and 1 ($n = 30$) TD group	No scales mentioned	To identify key Vertical Ground Reaction Forces (VGRF) gait features in ASD children	Eight-camera 3D motion capture system and two force plates	- 35-retroreflective markers bilaterally placed on children's bodies - Straight barefoot walking on a 6.5 m walkway with two force plates	- reduction of the second peak of VGRF ($p < 0.01$) for ASD children - lower push-off rate ($p < 0.05$) for ASD children - earlier relative time to the second peak of VGRF in ASD children - higher peak ratio in ASD children ($p < 0.01$) - no differences in walking speed and stance time	- no limitations mentioned
Bungariu N., de Weerd C., Young C., Longnecker R., Garver C., van Loon E., Rockenbach K., Patterson R. M. ³⁴	Motor function in children with Autism Spectrum Disorders	2013	14 children 2–12 years old	2 groups, 1 ($n = 7$) ASD and 1 ($n = 7$) TD group	- no scales mentioned	- to assess balance, walking, reaching and pointing out in ASD children	V-gait CAREN system (Computer Assisted Rehabilitation Environment Network) treadmill with a dual belt and integrated force plates 12 camera Motion Analysis System at 120 Hz	- two 30 s stance trials - one-minute walking on the treadmill - reaching and pointing out "target" (ducks) in Virtual Environments	- balance improves with increasing age - ASD children are less stable than TD children - higher variability of COP in ASD children - balance and walking improves slower in ASD group	- no limitations mentioned

(continued on next page)

Table 2 (continued)

Author	Manuscript	Year of publication, place	Participants	groups	Scales used	Purpose	Methodology	Procedure	Results	Limitations
Dufek J. S., Jeffrey Eggleston D., Harry R. J. and Hickman R. A. ³⁵	A Comparative Evaluation of Gait between Children with Autism and Typically Developing Matched Controls	2017	20 children 5–12 years old	2 groups, 1 (<i>n</i> = 10) ASD and 1 (<i>n</i> = 10) TD group	- no scales mentioned	- to compare gait characteristics in children ASD and TD children	eight-camera motion capture system (120 Hz; Vicon Motion Systems, Oxford, UK), one Kistler and two AMTI force platforms	- 19 retro-reflective markers placed bilaterally on childrens' bodies - 20 walking trials at a self-preferred speed	- decreased stability in ASD children - reduced ankle joint mobility (probably in a try for maintaining stability - larger magnitudes of joint motion variability in ASD children	- lack of ASD diagnosis verification - small range of gait categorisation - no pair matching for cognitive level of participants - no controlling of gait velocity - no limitations mentioned
Pauk J., Zawadzka N., Wasilewska A., Godlewski P. ³⁶	Gait Deviations in Children with Classic High-functioning Autism and Low-functioning Autism	2017	58 children	3 groups, 1 (<i>n</i> = 18) with high-functioning autism (HFA), 1 (<i>n</i> = 10) with Low-functioning Autism (LFA) AND 1 (<i>n</i> = 30) TD control group	- CARS - IQ measurement test	- to compare gait strategies between autism groups and controls	- optoelectronic system with six cameras, sampling at 60 Hz (SMART, BTS, Italy), and 2 Kistler (Kistler, model 9286AA-A, Kistler Instruments, Switzerland) platforms - a pedobrograph based on shoe insoles with capacitive sensors	- walking in self-preferred speed in three trials for TD children - walking toward an attractive toy (three to six trials) for ASD groups - plantar pressure was measured by walking 50 m in athletic shoes	- higher velocity (<i>p</i> = 0.005) and lower cadence in LFA compared to td group - no significant differences for stride length, step length, stance phase duration, double support - greater hip flexion in stance and swing for ASD groups - no significant group differences for anterior-posterior ground reaction and the mediolateral force - significant lower heel pressure for ASD groups	- no limitations mentioned
Yang C., Lee G., Lim Y., and Lim B. ³⁷	Comparative gait analysis between children with Autism and Age-matched controls	2014	30 children with mean age 11 years old	2 groups, 1 (<i>n</i> = 15) ASD and 1 (<i>n</i> = 15) TD group	- no scales mentioned	- to investigate gait in ASD children	- GAITrite® system	- after familiarization, children walked barefoot in self-preferred-speed on the 8-m walkway and stopped on the GAITrite pressure mat - three trials on average	- longer cycle time (<i>p</i> = 0.042), double support time (<i>p</i> = 0.004) stance time (<i>p</i> = 0.01), cadence (<i>p</i> = 0.048) for ASD group - slower normalized velocity (<i>p</i> = 0.009) and stride velocity (<i>p</i> = 0.038) for ASD children - wider step width (<i>p</i> = 0.008) and lower step/	- no limitations mentioned

(continued on next page)

Table 2 (continued)

Author	Manuscript	Year of publication, place	Participants	groups	Scales used	Purpose	Methodology	Procedure	Results	Limitations
--------	------------	----------------------------	--------------	--------	-------------	---------	-------------	-----------	---------	-------------

extremity ratio
($p = 0.017$) for
experimental
group

Abbreviations: ASD = Autism Spectrum Disorder, TD = Typically Developing, COP = Center Of Pressure, ASD Autism Spectrum Disorder, ADOS = Autism Diagnostic Observation Schedule, AQ-Child = Autism Spectrum Quotient: Child's Version, ATEC Autism Treatment Evaluation Checklist, CARS = Childhood Autism Rating Scale, ADI-R = Autism Diagnostic Interview-Revised, MABC = Movement Assessment Battery for Children, DCDQ = Developmental Coordination Disorder Questionnaire, CAREN = Computer Assisted Rehabilitation Network, IMUs = Inertial Measurement Units, GRF = Ground Reaction Forces, LFA = Low-Functioning Autism, HFA = High-Functioning Autism, VGRF = Vertical Ground Reaction Forces, TTB = Tip-Toe Behavior, CV = Coefficient of Variations, FSIQ = Full-Scale Intelligence Quotient, SRS = Social Responsiveness Scale, WPPSI-IV = Wechsler Preschool and Primary Scale of Intelligence-Forth Edition, SCQ = Social Communication Questionnaire, WISC = Wechsler Intelligence Scale for Children, WASI = Wechsler Abbreviated Scales of Intelligence, AQ = Autism Quotient checklist, CRP = Continuous Relative Phase, vCRP = Coordination Variability, MVIC = Maximal Voluntary Isometric Contractions.

gait parameters analysed in each study, such as stride length, step width, stability, postural control, gait speed, symmetry and joint mobility variables were identified. "Results section": The findings of each study were summarized, highlighting the key outcomes related to gait abnormalities in children with ASD. "Limitations": limitations of each study were documented to provide context for the interpretation of results and to identify areas for future research. In the included studies, the age of participants ranged from 4 to 12 years, with ASD diagnoses primarily established through the utilisation of DSM-5 or ICD-10/11 criteria. The majority of studies utilized motion capture systems or pressure-sensitive walkways, and analysed gait parameters including stride length, step width, cadence, and postural control. The majority of studies consistently reported increased step width and prolonged stance time in children with ASD, while smaller samples investigated joint mobility or asymmetry, often noting methodological limitations such as small sample sizes and heterogeneous protocols.

A synthesis of the included studies revealed that, while employing diverse designs and tools, the majority of studies converged on findings of increased step width and prolonged stance time in individuals with ASD. Furthermore, greater heterogeneity was observed in parameters such as joint mobility and asymmetry.

3.3. Characteristics of the participants

The inclusion criteria mandated the age range of participants to fall within childhood, specifically between 4 and 12 years old. This criterion ensured that the studies focused on developmental stages pertinent to gait analysis in children with ASD. Adolescents were included only if their data were part of studies that did not distinguish between children and adolescents.

The first and most frequently screened group deviation involved comparison between two groups. Most studies ($n = 11$) divided participants into two groups: one consisting of children diagnosed with ASD and one control group of typically developing (TD) children. This dichotomous grouping facilitated direct comparisons of gait parameters between children with ASD and their TD counterparts.^{5,13,21-23,31-35,37,41}

Between-groups deviation in three groups was facilitated in three studies. Gong et al.³⁰ and Pauk et al.³⁶ categorized participants based on their functional levels, including high-functioning ASD children, low-functioning ASD children, and a TD control group. This stratification enabled comparisons across functional levels (low-functioning, high-functioning and TD)⁰¹ Conversely, Li et al. segmented participants by age, creating three distinct groups: ages 6-8, 9-11, and 12-14 years. This age-based division enabled the researchers to examine developmental changes in gait parameters across different childhood stages. This age-matched deviation enabled analysis of developmental changes in gait analysis.²⁵

Homogeneity between participants was characteristic in three studies where groups were featured without significant demographic deviations and no control group was retrieved for these studies, composing one of studies' limitations.^{3,11,26}

These varying group classifications provided a comprehensive overview of gait patterns in children with ASD, accounting for potential variability due to age and functional level. This detailed approach allowed for more precise conclusions and the identification of specific gait abnormalities associated with different subgroups within the ASD population.

3.4. Diagnostic scales for ASD

- "Autism Diagnostic Observation Schedule (ADOS)": ADOS was employed in one investigation to ascertain ASD diagnoses.¹¹ ADOS is a direct observer measure of social interaction and communication behaviors, providing high reliability and validity.

- "Autism Spectrum Quotient: Children's Version (AQ-Child)": Utilized by Gong et al.,³⁰ this questionnaire quantitatively measures the extent of autistic traits in children 4–11 years old based on parents' reports.
- "Childhood Autism Rating Scale (CARS)": Employed by Pauk et al.,³⁶ CARS is a behavior-based rating system designed to identify and diagnose autism. Consisting of 14 domains assessing autistic behaviors and a 15th domain rating general impressions of ASD, total scores can range between 15 and 60, with higher scores indicating severe impairments.

3.5. Scales for motor assessment

In order to supplement the biomechanical evaluation of gait in children diagnosed with ASD, several studies have utilized standardised motor assessment tools. The scales employed were the following:

- Movement Assessment Battery for Children 2 (MABC-2): Biffi et al.²¹ and Manicolo et al.⁶ utilized this tool, which is designed to assess a range of motor skills and identify motor impairments in children and adolescents 3–16 years old, including new items, either revised or created compared to the previous version.
- Developmental Coordination Disorder Questionnaire (DCDQ): Also used by Biffi et al.,²¹ this parent-completed questionnaire assesses coordination and subtle motor difficulties in children between 8 and 14 years old, supplementing the findings from the MABC-2.

Despite the fact that these scales do not directly measure gait parameters, they offer complementary insights into the broader motor profile of children diagnosed with ASD. The utilisation of these metrics serves to enhance the interpretation of gait findings by situating them within the broader context of the participants' motor functioning.

3.6. Methods utilized for gait assessment

A variety of methodological approaches were employed to assess gait parameters in children with ASD across the studies:

- Observational/Report-Based Protocol: Valagussa et al.¹¹ utilized an observational/report-based assessment protocol to evaluate tip-toe behavior (walking/running/standing on tiptoes) in children with ASD. This dynamic (walking) and static (standing) test was conducted in a play environment under the supervision of a familiar therapist, with three trials recorded for each child. Children were instructed to stand and walk without shoes, only wearing their socks, on linoleum flooring. The child's motor behavior was video recorded from a floor perspective, depicting the region between the pelvis and the feet, in order to assess the gait parameters with greater accuracy. Three trials were taken into assessment for each child. The authors noted that the use of video recordings is subjective, as there is the possibility of variations in the evaluation of parameters between investigators.
- Plantar Pressure Measurements: Lim et al.³¹ and Gong et al.³⁰ employed plantar pressure measurements, with participants walking barefoot on an 8-m³³ or 6-m⁴⁰ carpet equipped with a plantar pressure mat. Children were first given the time to get familiarized with the environment. They were then instructed to walk on their personal speed. Gong et al. encouraged participants to walk while looking straight ahead at a paper cross hanging on the wall at a 0.9 m height. Where children seemed to struggle with the latest instruction, they were encouraged to keep their sight to their parents at the end of the walkway.
- Motion Capture Systems that were described in the studies include Vicon Motion Systems and Motion Analysis System with Dual Belt Instrumented Treadmill. Eggleston et al.³ and Olivas et al.²⁶ utilized a ten-camera three-dimensional motion capture system (Vicon

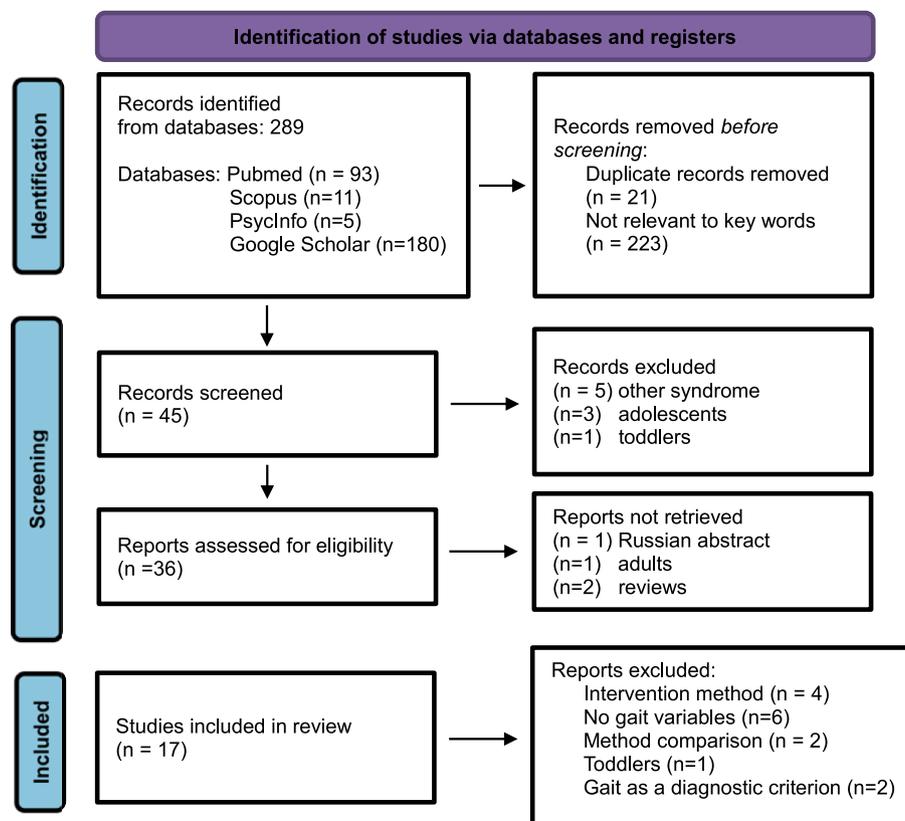


Fig. 1. The PRISMA statement of the articles that were excluded and included, according to the exclusion and inclusion criteria of the present review.

Table 3
Quality assessment of included studies by Newcastle-Ottawa Scale.

	SELECTION				COMPARABILITY	EXPOSURE		
	Adequate definition	Cases' representativeness	Controls' selection	Controls' definition		Comparability	Ascertainment of exposure	Same ascertainment method for cases and controls
Valagussa et al., 2024 ¹¹ 3/9	✓	✓	-	-	-	✓	-	-
Gong et al., 2020 ³⁰ 5/9	✓	-	-	-	✓✓	✓	✓	-
Olivas et al., 2022 ²⁶ 2/9	✓	-	-	-	-	✓	-	-
Lim et al., 2016 ³¹ 6/9	✓	✓	-	-	✓✓	✓	✓	-
Biffi et al., 2018 ²¹ 7/9	✓	✓	-	✓	✓✓	✓	✓	-
Manicolo et al., 2018 ⁶ 8/9	✓	✓	✓	✓	✓✓	✓	✓	-
Hasan et al., 2017 ¹³ 7/9	✓	✓	✓	✓	✓	✓	✓	-
Eggleston et al., 2018 ³ 2/9	✓	-	-	-	-	✓	-	-
Eggleston et al., 2020 ²² 5/9	✓	-	-	✓	✓	✓	✓	-
Li et al., 2021 ²⁵ 3/9	✓	✓	-	-	-	✓	-	-
Shetreat-Klein et al., 2014 ²³ 8/9	✓	✓	✓	✓	✓✓	✓	✓	-
Wu et al., 2024 ³² 6/9	✓	-	-	✓	✓✓	✓	✓	-
Hasan et al., 2018 ³³ 8/9	✓	✓	✓	✓	✓✓	✓	✓	-
Bungariu et al., 2013 ³⁴ 5/9	✓	✓	-	-	✓	✓	✓	-
Dufek et al., 2017 ³⁵ 6/9	✓	-	-	✓	✓✓	✓	✓	-
Pauk et al., 2017 ³⁶ 5/9	✓	-	-	✓	✓	✓	✓	-
Yang et al., 2014 ³⁷ 5/9	✓	-	-	-	✓✓	✓	✓	-

Motion Systems), with spherical retro-reflective markers placed bilaterally on the children's bodies. Participants were instructed to walk on a dynamic-force pressure walkway. Olivas et al. instructed their participants to walk at three speed conditions (self-preferred speed, faster and slower than their preferred speed) in order to examine the speed influence on participants' gait variations whereas Eggleston et al. differentiated their examination conditions by weight. Children walked at their preferred speed on the walkway in the first condition and they were then loaded with a weighted vest 15% of their body mass. These conditions aimed to enlighten the differences in walking patterns with and without weight. Wu et al. employed a 15-camera Vicon Motion Capture system, and the walking task was performed on an AMTI force treadmill with force plates to capture 3D ground reaction forces at a frequency of 2 000 Hz. Twenty-two retroreflective markers were placed on the

participants' compression garments. Participants were asked to walk on the treadmill to familiarize themselves with the procedure and then walked at a constant speed for 5 min. After a 5 min rest, they were instructed to perform maximal voluntary isometric contractions on a Cybex dynamometer to measure knee muscle strength.³² Pradhan et al.⁴¹ and Bungariu et al.³⁴ utilized Vicon Motion Systems with 12-camera while Eggleston et al.,²² Hasan et al.³³ and Dufek et al.³⁵ 8-camera configurations, respectively.^{22,41} Children walked at a self-preferred speed. Biffi et al.²¹ employed a 3-D motion analysis system with a dual-belt, instrumented treadmill to assess gait parameters. In this study, children walked for 6 min capturing 20 steps under evaluation. Afterwards a discrete perturbation was implemented during walking by the dual belt system. Steps during and after perturbation were also recorded aiming to assess the perturbation's impact on children's motor performance.²¹ Optoelectronic

system with six cameras, sampling at 60 Hz was implemented by Pauk et al.³⁶ in a laboratory environment. V-gait CAREN (Computer Assisted Rehabilitation Environment Network) system treadmill with a dual belt and integrated force plates was used by Bungariu et al.³⁴ which can be utilized either in self-preferred speed or in speed selected by the researchers. Perturbations can also be implemented during the walking measurement.³⁴

- Other Gait Measurement Methods retrieved from the studies involve the GAITRite electronic walkway system, AMTI force platform, video recordings, Force Plates and pedobarograph. Manicolo et al.⁶ and Yang et al.³⁷ utilized the GAITRite electronic walkway system to evaluate spatio-temporal gait parameters, base of support and variability, while Dufek et al.³⁵ preferred an AMTI force platform for postural control assessment. Li et al.²⁵ utilized Inertial Measurement Units (IMUs) to qualify spatiotemporal gait parameters in relation with age maturation and Shetreat-Klein et al.²³ conducted video recordings during walking in an adjusted physician's office in order to assess joint mobility in children with ASD. The Force Plates were used by Hasan et al.¹³ which primarily utilized force plates to measure stability and ground reaction forces during gait assessments. Kistler force plates were preferred by Dufek et al.³⁵ and Pauk et al.³⁶ for joint mobility and kinetics respectively. Pauk et al.³⁶ also supplemented the methodology with a pedobarograph based on shoe insoles with capacitive sensors for plantar pressure assessment.

These diverse methodologies were implemented across studies to encompass diverse aspects of gait performance in children with ASD. Each of the aforementioned methods was focused on a different set of aspects of gait performance, for instance, spatiotemporal parameters, joint kinematics, or kinetic outputs.

Across these methodologies, the studies consistently reported altered gait patterns in children with ASD, such as slower walking speed, increased step width, longer stance times, and reduced joint range of motion. Kinetic analyses further revealed diminished ground reaction forces and challenges in adapting to perturbations, suggesting a reduced capacity for gait adaptability in comparison to TD peers.

3.7. Summary of findings

The synthesis of findings indicates that some gait parameters, such as increased step width, prolonged stance/double support time, and decreased stability, are consistently reported across studies. In contrast, parameters such as stride length, cadence, gait speed, joint range of motion, symmetry, and tip-toe behaviour have yielded contradictory results, which is likely attributable to methodological differences, sample heterogeneity, and variability in assessment tools (Table 4).

4. Discussion

This study represents a pioneering effort in aggregating the myriad observations regarding gait patterns in children diagnosed with ASD. Gait analysis, encompassing both kinetic and kinematic parameters, serves as a window into understanding deviations from typical locomotor patterns. While kinematics delineates bodily movements, kinetics delves into the underlying forces and moments driving motion.¹³ Kinetic features have the potential to contribute to the accurate and interpretable classification of autism and control patterns in children.⁴¹

The complexity of gait as an understudied variable in ASD is also distinguished by the wide variety of parameters studied in each research examining gait. In several studies, step width, a frequently studied parameter, was found wider for autistic children^{22,31,37} whereas other researchers focused on step length confirming shorter steps in ASD.^{6,22,32} Lim et al.,³¹ Yang et al.³⁷ and Wu et al.³² investigated cadence which was derived to be lower for experimental group in the first study but greater in the last one whilst other studies delved into asymmetry as an examined parameter concluding in more asymmetrical

patterns in ASD children.^{3,26,30} Toe-walking was also examined as a clinically present behavior in children with ASD, although not concluding consistent findings.^{11,23,30} Lim et al.³¹ and Yang et al.³⁷ found longer cycle time in children with ASD, whereas Olivas et al.²⁶ focused on joint mobility concluding in increased knee extension in children with ASD. Joint mobility was also studied by Li et al.²⁵ and Olivas et al.²⁶ coming in agreement regarding the increased knee flexion and increased ankle dorsiflexion. Results were conflicting for dorsiflexion, as Lim et al.³¹ found increased dorsiflexion, whereas Olivas et al.²⁶ decreased ankle dorsiflexion. The set of surveys agreed in varied Ground Reaction Forces (GRF) used by children with ASD.^{13,21,33,32}

Our synthesis reveals a nuanced landscape of findings across various gait parameters, discussed below in detail.

4.1. Spatio-temporal gait parameters

Regarding step width, findings indicate a statistically significant wider step width ($p = 0.008$) in children with ASD compared to their typically developing counterparts.^{31,37} Eggleston et al. as also Wu et al. noted a divergence, reporting substantially higher magnitudes of stride width variability in children with ASD.^{22,32} Stride length, described as the distance between the heel points of two successive steps of the same foot,⁶ was found with no significant differences compared to TD peers^{6,22} whereas Wu et al.³² revealed a shorter stride length (6% shorter, $p = 0.03$) in ASD children. These discrepancies can be attributed to methodological and sample-related differences. Firstly, a conspicuous disparity was observed in the age ranges: Manicolo et al.⁶ examined children aged 4–17 and Eggleston et al.²² 5–12, whereas Wu et al.³² focused exclusively on older children (9–17 years), potentially capturing developmental changes that influence stride characteristics. Secondly, a variety of measurement tools were utilized. Manicolo et al. employed the GAITRite electronic walkway system, which captures spatiotemporal parameters on flat surfaces in a linear path, while Wu et al. utilized a high-resolution 15-camera Vicon motion capture system, which may provide more sensitive kinematic data in three dimensions. Thirdly, the observed discrepancy in sample size, with the former study⁶ comprising of 68 and the latter of 22 participants,³² has the potential to influence statistical power and the detection of effects. It should also be underlined that as researchers state, the same results in spatiotemporal variables between the groups while they appear to have differences in gait variability, emphasizes the significance of incorporating variability measures as they may provide a more accurate and sensitive measure of gait performance.⁶ Biffi et al. also indicate a tendency to shorter step length in ASD children, though not statistically significant ($p = 0.371$)²¹ while Pauk et al. found no difference in step length between Low-Functioning Autism (LFA), High-Functioning Autism (HFA) and TD

Table 4
Summary of findings.

Gait Parameter	Consistent Findings in ASD	Conflicting/Inconsistent Findings
Step width	Increased compared to TD	–
Stride length	–	Shorter vs no difference
Cadence	–	Lower vs higher
Gait speed	–	Reduced vs no difference
Stance time/Double support	–	Prolonged time vs no difference in some studies
Joint range of motion	–	Increased vs decreased (ankle, knee)
Variability	Increased gait variability	–
Symmetry	–	Increased vs unchanged
Stability	Decreased stability during gait	–
Tip-toe behavior	–	Higher prevalence vs flat-foot patterns

group.³⁶ Concerning stride time, no difference was retrieved between children with ASD and controls.⁶ Stride velocity was significantly slower ($p = 0.038$) in the ASD group compared to their typical controls.^{31,37}

Consistent findings across studies indicate a longer cycle time, “defined as time elapsed from the first contacts of two consecutive footprints of the same foot”³¹ in children with ASD compared to control groups and especially statistically significant longer ($p = 0.042$).^{31,37} Double support time was also found significantly longer ($p = 0.004$) for children with ASD in a comparative gait analysis study.³¹ In the study of Lim et al., stance time was recorded significantly lower ($p = 0.01$) in ASD group related to TD control group,³¹ whereas Hasan et al. found no significant group differences between ASD and TD children.³³

Up to cadence (steps per minute),⁴ lower levels observed in children with ASD reflects a slower walking pace relative to typically developing peers in self-preferred walking speed.^{31,37} However, Wu et al. revealed an increased cadence rate in children with ASD at 8% compared to control group.³² This difference might be attributed to different research procedures. Wu et al. asked children to accelerate through the process while the rest studies did not imply speed alterations.

Overall, spatio-temporal analyses indicate that children with ASD exhibit wider step width, longer cycle times, and slower stride velocity. However, findings concerning stride length and cadence remain inconsistent across studies.

4.2. Gait force parameters

Lim et al. examined pressure variables and retrieved statistically lower segmental integrated pressure over time in the hind foot ($p = 0.023$) for the ASD group, as well as lower active area of pressure in the hind foot ($p = 0.039$). Peak pressure was also statistically lower ($p = 0.002$) and peak pressure times were in general later in children with ASD compared to TD control group.³¹

Ground reaction forces (GRF), the most essential force in gait analysis, refers to the force exerted by the ground on the foot and supports the body against gravity and accelerates the body's center of mass during gait.¹³ Variability in anterior-posterior and vertical ground reaction force patterns underscores the unique gait dynamics observed in children with ASD.^{13,33} The maximum braking force of the anterior-posterior GRF was significantly higher in children with ASD ($p = 0.029$). Research group displayed a tendency, even not statistically significant ($p = 0.07$), in applying smaller (4% less) vertical GRF during the push-off phase and a significant ($p = 0.03$) larger (14%) Antero-posterior braking GRF compared to their typically developing children.³² Notably, children with ASD exhibit distinct strategies, such as increased ground reaction forces at the ankle to maintain stability during perturbed locomotion.²¹ The second peak of Vertical Ground Reaction Forces (VGRF) was recorded significantly reduced for ASD children ($p < 0.01$) as well as the push-off rate ($p < 0.05$). The relative timing of the second peak of VGRF occurs at an earlier point in the gait cycle for children with ASD, indicating a significant difference compared to typically developing individuals. The peak ratio was found notably greater in children with ASD.³³

Significantly wider base of support ($p < 0.001$) observed in children with ASD underscores the altered gait dynamics in this population.⁶

In Gong's et al. study, ASD children (high- and low-functioning) when compared to their matched typical controls, revealed an abnormal force distribution when walking forward, producing less forefoot and more hind foot force.³⁰

In summary, children with ASD exhibit divergent force patterns during gait, thus emphasizing the implementation of distinct compensatory strategies.

4.3. Tip toe behavior

The prevalence of toe walking, or “Tip-toe behavior” (TTB) as proposed by Valagussa et al.,¹¹ a noted clinical observation, remains

contentious in the literature. Gong et al. did not find a higher prevalence of toe walking in children with ASD but observed a “flat-footed” pattern among autistic children.³⁰ Valagussa et al. divided the sample into three groups according to tip-toe behavior: one group that showed TTB only during running, one during walking and running, and one during walking, running, and standing. Their findings implicate that children who showed TTB during walking, running and standing, utilized this pattern more frequently than the other two groups. Consequently, children from the second group, showed TTB more often than the first group. It should also be underlined that the majority of the sample were diagnosed with Intellectual Disability which, after the multivariable analysis, was found to be statically related TTB ($p < 0.001$).¹¹ By contrast, Shetreat et al. reported a significantly higher incidence ($p = 0.001$).²³ It is noteworthy that the methodology employed in the two subsequent studies was based on video recording, in contrast to Gong et al.³⁰ where the assessment was conducted using a plantar pressure mat highlighting methodological questions. The extant literature on the prevalence of toe walking in ASD remains inconsistent, with findings being influenced by factors such as sample characteristics and methodological differences.

4.4. Gait variability

Manicolo et al. studied gait in children with atypical/infantile autism. This group exhibited significantly higher gait variability compared to children without ASD. Gait variability was also correlated with motor skills revealing significant differences in gait variables through Coefficient of Variations (CV). More specifically, lower scores in M-ABC-2 were associated with lower scores in all gait variability scores (CV stride velocity $p = 0.016$, CV stride time $p = 0.045$ and CV stride length $p = 0.027$). Age was also associated through regression analysis with lower gait variability scores unveiling significant differences in all gait variables, CV stride velocity $p = 0.004$, CV stride time $p = 0.002$ and CV stride length $p = 0.002$.⁶ Overall, gait variability appears to be enhanced in individuals diagnosed with ASD, and this variability is closely associated with the level of motor skills exhibited by the individual, as well as their age.

4.5. Joint mobility

Increased hip extension ($p = 0.001$) as well as knee flexion, particularly under conditions of increased walking speed, was observed in children with ASD.^{25,26} Less knee flexion was observed in older children, thus providing impetus for further investigation into the influence of age on motor performance.³²

Regarding the knee extension, after the application of discrete gait perturbations, ASD participants increased their knee extension in an effort to proximalize the control of their lower limbs.²¹

Concerning the ankle, while some studies observed significant increased ankle dorsiflexion ($p < 0.01$) in children with ASD,²⁵ others noted a decrease in dorsiflexion in PS-w under conditions of increased walking speed, though without a typically developed control group comparison.²⁶ In loaded conditions, ankle joint position was not significantly influenced.³

The findings on joint mobility in ASD are inconsistent, suggesting that age as well as task conditions have a significant influence on lower-limb kinematics.

4.6. Stability

Decreased stability remains a constant conclusion among the research outputs,^{34,35} and yet, it is recommended that balance improves slower in children with ASD comparing to their neurotypical peers.³⁴ Children with ASD demonstrate unique adaptations to maintain stability during perturbations, including alterations in walking speed and impaired coordination of joint processes.^{21,35}

4.7. Asymmetry

Consistency between research shows that increased left-right asymmetry, coupled with asymmetrical movement patterns under external load conditions, characterizes gait abnormalities in children with ASD.^{3,30} Asymmetry was not confirmed by Li et al.²⁵ attributed by the authors to heterogeneities in the sample (age, height, body mass).

4.8. Speed

Regarding their walking speed, Manicolo et al. did not find significant differences between ASD and control group.^{6,33} Speed was also employed as a study variable in order to examine the effect of altering speed (walking faster or at their preferred speed) on gait parameters,^{11,26} leading to the conclusion that when gait speed is altered, the ankle joint is the primary kinematic strategy applied by children with ASD.²⁶

4.9. Age

Age is mentioned in the present section as two studies examined age as a co-variable under examination related to gait parameters. It was indicative of motor milestones as children with ASD walk autonomously later than typically developing children although early motor milestones, like sitting upright, do not seem to be indicative of later gait development during childhood.^{6,23}

4.10. Social and communicative impact

Research has progressively focused on the nature of perceptual-motor impairments, highlighting their impact on the social, communication and behavioural skills of individuals with ASD.⁵ Walking, as a primary activity, plays a vital role in the progressive development of children's communication skills.¹⁷ However, restricted motor development in ASD individuals can severely limit their ability to participate in activities of daily living and team sports.⁵ The ability to perform everyday tasks, such as maintaining postural control and coordinating movements towards a goal, is essential for promoting social interactions, communication skills and play.¹⁷ Therefore, these well-documented motor skill deficiencies are thought to contribute significantly to the social impairments that characterize individuals with ASD.⁹ It has been shown that children with ASD have various types of movement impairments that adversely affect their daily physical activities, specifically gait.¹³ These motor disorders are clinically significant because they can interfere with participation in activities that are critical for the development of age-appropriate behavioral, cognitive, social and communication skills.⁵ In addition, motor difficulties can affect participation in physical activities that are essential for optimal health and well-being.¹¹

4.11. Previous literature review conclusions

In recent years, there have been numerous attempts to conduct scientific studies on the subject of gait in ASD children. The results of these studies have largely corroborated the findings of the present study. Motor performance in ASD children is characterized by significant qualitative and quantitative differences in comparison to neurotypical children, with substantial impairments observed in motor coordination and postural control.⁸ As demonstrated by the findings of the present review, individuals diagnosed with ASD generally demonstrate reduced coordination.^{8,27} The presence of motor coordination deficits is pervasive, suggesting that these deficits are a fundamental symptom of ASD.²⁷ Children with ASD have been observed to exhibit increased step width, and, albeit controversially, decreased step length and stride length.^{4,7} A longer double support time, stance time, and step time are observed in children with autism, indicating a less fluid and more effortful gait.

However, no significant differences were found in gait cycle time.⁷ Older ASD groups tend to have longer gait cycle times and slower cadences, but age is not associated with a direct impact on stride length.⁷ While ASD does not universally affect all parameters of gait, the findings indicate a consistent pattern of motor coordination difficulties, which may reflect a more rigid and less adaptive movement pattern overall.⁷

4.12. Limitations of evidence included in the review

A secondary aim of this review was to identify the limitations of all studies in order to provide directions for future research. A small sample size was a difficulty in most studies, eliminating the generalizability of research findings. A further limitation is the lack of control groups. It is established that children with ASD exhibit variations in gait pattern. However, a control group is of utmost necessity to make a more accurate comparison and to identify potential avenues for intervention and improvement. Another issue is the functioning level of ASD research groups. As autism is a broad spectrum disorder, the symptoms of a child with low-functioning ASD differ significantly compared to those of a child with high-functioning ASD. Most studies included only high-functioning children, thus restricting the knowledge about low-functioning children's motor impairment.

4.13. Scope for future studies

One of the most imperative needs for future studies is to include participants from across the spectrum and imply a group deviation based on participants' functional level. It is also important to consider the issue of medication, as there is likely to be an effect on individuals' mobility. These effects are urgently needed to be identified in order to avoid adverse effects or to be used for the benefit of children. The physical fitness of participants should also be considered, as different levels of fitness will also lead to heterogeneous results.

A comparison of the studies reveals discrepancies in the findings when the participants' age differs, underscoring the necessity of considering age as a crucial research variable. It is argued that as children with ASD move into adulthood, the motor variations in their gait pattern become blunted over time. However, it is important that improvement is pursued throughout the school life of individuals to avoid any form of exclusion due to their motor deficits.

Another issue concerning methodology issues is related to the type of method applied as some studies use observation methods, while others use video recording. Similarly, some utilize plantar pressure mats, while others employ motion capture systems. Differences in methodological approaches lead to differences in results obtained. It is therefore important that similar research methods are used in order to facilitate comparison and enhance the validity of research results.

It is also important to highlight that, although studies have indicated a correlation between motor deficits and social deficits in children with ASD, there is currently a lack of comprehensive research that accurately elucidates this interaction. It is imperative that future studies are designed to examine this relationship more closely in order to contribute to the development of more effective and personalized treatment plans.

5. Conclusions

The amalgamation of findings underscores the complexity of gait abnormalities in children with ASD. While certain parameters exhibit consistent deviations from normative values, discrepancies persist across studies. Methodological variations, participant characteristics, and sample size limitations contribute to this heterogeneity. Although a variety of methods provide a wide range of results on the complex function of gait, it is important that research methods are carefully designed. For example, gait analysis systems, such as the GAITrite plantar pressure mat, offer significant advantages in the investigation of motor function, particularly in populations such as autistic children. The

authors assert that the GAITrite system exhibits high reliability and validity, thereby establishing it as a robust research tool. The system's ease of use, minimal preparation, and non-invasive nature are particularly beneficial for autistic children, who may experience difficulties in unfamiliar environments and exhibit heightened sensory sensitivities. However, the system has certain limitations. For instance, it is unable to analyse the relationship between lower-limb kinematics and plantar pressure. While force plates are able to measure ground reaction forces, they are unable to capture muscle activity. Video recordings, despite their widespread use, present subjective inconsistencies in clinical scoring. Furthermore, although motion capture systems are informative, they are often impractical for autistic children due to their complexity and the sensory challenges posed by reflective markers.

Regarding the research groups, the nature of the sample is unique, but small participant sizes limit the generalizability of the results. Another issue that usually arises is the functional level of the participants. Low-functioning children are usually excluded because of their inability to understand and perform the procedures. However, since in most studies the level of motor deficits seems to be related to the core symptoms of ASD, it would be important to find a way to adapt the measurement methods to the level of the whole functional spectrum or to try to identify methods that are applicable and suitable for children across the whole spectrum.

The results of the studies reviewed indicate that the gait of children with ASD exhibits notable differences compared to their typically developing peers. These include difficulties in maintaining balance, an increased step width and length, challenges in stability, difficulties in adapting to changes in speed or weight bearing, alterations in joint mobility, particularly in the knee and ankle joints. These data are particularly useful for clinicians involved in the diagnostic process (psychiatrists, psychologists, special educators, paediatricians) and for staff engaged in the therapeutic design of interventions for children with ASD (occupational therapists and psychologists). A comprehensive understanding of the spectrum of motor deficits enables mental health workers to make accurate and timely diagnoses and to develop more effective treatment plans. For instance, an occupational therapist may focus on enhancing these deficits with the objective of improving the child's daily functioning and social integration. Additionally, parents may be encouraged to engage in sports activities that facilitate the development of skills such as balance and stability, including gymnastics or dance. With an accurate diagnosis and early intervention, motor deficits can be addressed and the impact on children's lives (exclusion from team sports, difficulties in daily functioning) can be reduced.

In addition to conventional biomechanical approaches, recent literature has highlighted emerging technologies with potential relevance to gait research in ASD. For instance, 3D printing has been increasingly applied in the development of customised footwear and orthoses, demonstrating the capacity to redistribute plantar pressures and improve comfort, although evidence for long-term efficacy remains limited.⁴² In a similar vein, the integration of wearable sensors with machine learning algorithms has demonstrated efficacy in the identification of atypical movement patterns and stress-related physiological changes in children diagnosed with ASD. This finding supports the hypothesis that the incorporation of AI-driven analytics into gait assessment and intervention protocols holds significant potential.^{43,44} These technological innovations, while still in the early stages of development, highlight future opportunities for more individualised, objective, and scalable approaches to the study and management of motor impairments in ASD.

Robust investigations, accounting for these factors, are imperative to unravel the intricacies of gait dysfunction in ASD. Enhanced understanding holds promise for tailored interventions and improved clinical management strategies. Thus, the imperative for further research in this domain persists, offering avenues for advancing our comprehension of motor impairments in ASD and guiding targeted interventions.

CRediT authorship contribution statement

Aikaterini Ioannidou: Writing – review & editing, Writing – original draft, Project administration, Methodology, Formal analysis, Data curation. **Pinelopi Vlotinou:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Data curation, Conceptualization. **Anna Tsiakiri:** Validation, Resources, Project administration. **Nikolaos Aggelousis:** Supervision, Resources. **Georgios Labiris:** Supervision, Project administration. **Aspasia Serdari:** Supervision, Project administration.

Manuscript registration statement

The current review was conducted and reported with the guidance of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) statement.²⁹ The present study is prospectively registered with PROSPERO (PROSPERO registration number: CRD42024583687).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.smhs.2025.11.002>.

References

- World health organization. *ICD-11*; January 1, 2024. <https://icd.who.int/browse/2024-01/mms/en#437815624>. Accessed September 5, 2024.
- Center for Disease Control and Prevention. Data and statistics on autism spectrum disorder. <https://www.cdc.gov/autism/data-research/index.html>; May 16, 2024. Accessed September 5, 2024.
- Eggleston JD, Landers MR, Bates BT, Nagelhout E, Dufek JS. Examination of gait parameters during perturbed over-ground walking in children with autism spectrum disorder. *Res Dev Disabil*. 2018;74:50–56. <https://doi.org/10.1016/j.ridd.2018.01.004>.
- Kindregan D, Gallagher L, Gormley J. Gait deviations in children with autism spectrum disorders: a review. *Autism Res Treat*. 2015;2015(1):741480. <https://doi.org/10.1155/2015/741480>.
- Kaur M, Srinivasan SM, Bhat AN. Comparing motor performance, praxis, coordination, and interpersonal synchrony between children with and without Autism Spectrum Disorder (ASD). *Res Dev Disabil*. 2018;72:79–95. <https://doi.org/10.1016/j.ridd.2017.10.025>.
- Manicolo O, Brotzmann M, Haggmann-von Arx P, Grob A, Weber P. Gait in children with infantile/atypical autism: age-dependent decrease in gait variability and associations with motor skills. *Eur J Paediatr Neurol*. 2019;23(1):117–125. <https://doi.org/10.1016/j.ejpn.2018.09.011>.
- Lum JA, Shandley K, Albein-Urios N, et al. Meta-analysis reveals gait anomalies in autism. *Autism Res*. 2021;14(4):733–747. <https://doi.org/10.1002/aur.2443>.
- Bhat AN, Landa RJ, Galloway JC. Current perspectives on motor functioning in infants, children, and adults with autism spectrum disorders. *Phys Ther*. 2011;91(7):1116–1129. <https://doi.org/10.2522/ptj.20100294>.
- Martín-Díaz P, Carratalá-Tejada M, Molina-Rueda F, Cuesta-Gómez A. Reliability and agreement of the timed up and go test in children and teenagers with autism spectrum disorder. *Eur J Pediatr*. 2023;182(8):3577–3585. <https://doi.org/10.1007/s00431-023-05027-8>.
- Uljarević M, Hedley D, Alvares GA, Varcin KJ, Whitehouse AJ. Relationship between early motor milestones and severity of restricted and repetitive behaviors in children and adolescents with autism spectrum disorder. *Autism Res*. 2017;10(6):1163–1168. <https://doi.org/10.1002/aur.1763>.
- Valagussa G, Purpura G, Balatti V, Trentin L, Signori A, Grossi E. Quantitative assessment of tip-toe behavior in individuals with autism spectrum disorder and intellectual disability: a cross-sectional study. *Autism Res*. 2024;17(2):311–323. <https://doi.org/10.1002/aur.3072>.

12. Goldman S, Wang C, Salgado MW, Greene PE, Kim M, Rapin I. Motor stereotypies in children with autism and other developmental disorders. *Dev Med Child Neurol*. 2009;51(1):30–38. <https://doi.org/10.1111/j.1469-8749.2008.03178.x>.
13. Hasan CZC, Jailani R, Tahir NM, Ilias S. The analysis of three-dimensional ground reaction forces during gait in children with autism spectrum disorders. *Res Dev Disabil*. 2017;66:55–63. <https://doi.org/10.1016/j.ridd.2017.02.015>.
14. Longuet S, Ferrel-Chapus C, Orève MJ, Chamot JM, Vernazza-Martin S. Emotion, intent and voluntary movement in children with autism. An example: the goal directed locomotion. *J Autism Dev Disord*. 2012;42(7):1446–1458. <https://doi.org/10.1007/s10803-011-1383-x>.
15. Nayate A, Bradshaw JL, Rinehart NJ. Autism and asperger's disorder: are they movement disorders involving the cerebellum and/or basal ganglia? *Brain Res Bull*. 2005;67(4):327–334. <https://doi.org/10.1016/j.brainresbull.2005.07.011>.
16. Nayate A, Tonge BJ, Bradshaw JL, McGinley JL, Iansek R, Rinehart NJ. Differentiation of high-functioning autism and asperger's disorder based on neuromotor behavior. *J Autism Dev Disord*. 2012;42:707–717. <https://doi.org/10.1007/s10803-011-1299-5>.
17. Armitano-Lago C, Bennett HJ, Haegele JA. Lower limb proprioception and strength differences between adolescents with autism spectrum disorder and neurotypical controls. *Percept Mot Skills*. 2021;128(5):2132–2147. <https://doi.org/10.1177/00315125211036418>.
18. Bennett HJ, Jones T, Valenzuela KA, Haegele JA. Inter and intra-limb coordination variability during walking in adolescents with autism spectrum disorder. *Clin Biomech*. 2021;89:105474. <https://doi.org/10.1016/j.clinbiomech.2021.105474>.
19. Esposito G, Venuti P, Apicella F, Muratori F. Analysis of unsupported gait in toddlers with autism. *Brain Dev*. 2011;33(5):367–373. <https://doi.org/10.1016/j.braindev.2010.07.006>.
20. Eggleston JD, Landers MR, Bates BT, Nagelhout E, Dufek JS. Weighted walking influences lower extremity coordination in children on the autism spectrum. *Percept Mot Skills*. 2018;125(6):1103–1122. <https://doi.org/10.1177/0031512518803178>.
21. Biffi E, Costantini C, Ceccarelli SB, et al. Gait pattern and motor performance during discrete gait perturbation in children with autism spectrum disorders. *Front Psychol*. 2018;9:2530. <https://doi.org/10.3389/fpsyg.2018.02530>.
22. Eggleston JD, Harry JR, Cereceres PA, et al. Lesser magnitudes of lower extremity variability during terminal swing characterizes walking patterns in children with autism. *Clin Biomech*. 2020;76:105031. <https://doi.org/10.1016/j.clinbiomech.2020.105031>.
23. Shetreat-Klein M, Shinnar S, Rapin I. Abnormalities of joint mobility and gait in children with autism spectrum disorders. *Brain Dev*. 2014;36(2):91–96. <https://doi.org/10.1016/j.braindev.2012.02.005>.
24. Wilson RB, Burdekin ED, Jackson NJ, et al. Slower pace in early walking onset is related to communication, motor skills, and adaptive function in autistic toddlers. *Autism Res*. 2024;17(1):27–36. <https://doi.org/10.1002/aur.3067>.
25. Li Y, Koldenhoven RM, Liu T T, Venuti CE. Age-related gait development in children with autism spectrum disorder. *Gait Posture*. 2021;84:260–266. <https://doi.org/10.1016/j.gaitpost.2020.12.022>.
26. Olivas AN, Kendall MR, Parada A, Manning R, Eggleston JD. Children with autism display altered ankle strategies when changing speed during over-ground gait. *Clin Biomech*. 2022;100:105804. <https://doi.org/10.1016/j.clinbiomech.2022.105804>.
27. Fournier KA, Hass CJ, Naik SK, Lodha N, Cauraugh JH. Motor coordination in autism spectrum disorders: a synthesis and meta-analysis. *J Autism Dev Disord*. 2010;40:1227–1240. <https://doi.org/10.1007/s10803-010-0981-3>.
28. Bennett HJ, Ringleb SI, Bobzien J, Haegele JA. Walking lower extremity biomechanics of adolescents with autism spectrum disorder. *J Biomech*. 2021;119:110332. <https://doi.org/10.1016/j.jbiomech.2021.110332>.
29. Page MJ, McKenzie JE, Bossuyt PM, et al. The prisma 2020 statement: an updated guideline for reporting systematic reviews. *Br Med J*. 2021;372:n71. <https://doi.org/10.1136/bmj.n71>.
30. Gong L, Liu Y, Yi L, Fang J, Yang Y, Wei K. Abnormal gait patterns in autism spectrum disorder and their correlations with social impairments. *Autism Res*. 2020;13(7):1215–1226. <https://doi.org/10.1002/aur.2302>.
31. Lim BO, Sullivan D, Choi BG, Kim MY. 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(1):286–292. <https://doi.org/10.1589/jpts.28.286>.
32. Wu X, Dickin DC, Bassette L, Ashton C, Wang H. Clinical gait analysis in older children with autism spectrum disorder. *Sports Med Health Sci*. 2024;6(2):154–158. <https://doi.org/10.1016/j.smhs.2023.10.007>.
33. Hasan CZC, Jailani R, Tahir NM, Desa HM. Vertical ground reaction force gait patterns during walking in children with autism spectrum disorders. *J Eng Trans B Appl*. 2018;31(5):705–711. <https://doi.org/10.5829/ije.2018.31.05b.04>.
34. Bugnariu N, de Weerd C, Young C, et al. Motor function in children with autism spectrum disorders. In: *The 2013 International Conference on Virtual Rehabilitation (ICVR)*. IEEE; 2013:51–56. <https://doi.org/10.1109/ICVR.2013.6662080>.
35. Dufek JS, Eggleston JD, Harry JR, Hickman RA. A comparative evaluation of gait between children with autism and typically developing matched controls. *Med Sci*. 2017;5(1):1–11. <https://doi.org/10.3390/medsci5010001>.
36. Pauk J, Zawadzka N, Wasilewska A, Godlewski P. Gait deviations in children with classic high-functioning autism and low-functioning autism. *J Mech Med Biol*. 2017;17(3):1750042. <https://doi.org/10.1142/S0219519417500427>.
37. Yang CS, Lee GS, Lim YT, Lim BO. Comparative gait analysis between children with autism and age-matched controls. In: *The 32nd International Conference of the International Society of Biomechanics in Sports (ISBS)*. 2014:817–820.
38. The Ottawa Hospital. The Newcastle-Ottawa Scale (NOS) for assessing the quality of nonrandomised studies in meta-analyses. https://www.ohri.ca/programs/clinical_epidemiology/oxford.asp; May 3, 2021. Accessed September 20, 2024.
39. Lo CKL, Mertz D, Loeb M. Newcastle-ottawa scale: comparing reviewers' to authors' assessments. *BMC Med Res Methodol*. 2014;14:1–5. <https://doi.org/10.1186/1471-2288-14-45>.
40. Luchini C, Stubbs B, Solmi M, Veronese N. Assessing the quality of studies in meta-analyses: advantages and limitations of the newcastle ottawa scale. *World J Meta-Anal*. 2017;5(4):80–84. <https://doi.org/10.13105/wjma.v5.i4.80>.
41. Pradhan A, Chester V, Padhiar K. Classification of autism and control gait in children using multisegment foot kinematic features. *Bioengineering*. 2022;9(10):552. <https://doi.org/10.3390/bioengineering9100552>.
42. Lu Z, Li X, Sun D, et al. Will this be the next step? A systematic review of 3D printing in footwear biomechanics. *Footwear Sci*. 2025;17(2):127–142. <https://doi.org/10.1080/19424280.2025.2472251>.
43. Khera P, Kumar N. Role of machine learning in gait analysis: a review. *J Med Eng Technol*. 2020;44(8):441–467. <https://doi.org/10.1080/03091902.2020.1822940>.
44. Arbili O, Rokach L, Cohen S. Wearable sensors for ensuring sports safety in children with Autism Spectrum Disorder: a comprehensive review. *Sensors*. 2025;25(5):1409. <https://doi.org/10.3390/s25051409>.