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Sensory Integration and Praxis Characteristics in Children with Idiopathic Toe Walking: A Case–Control Study

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Abstract

Aims: Idiopathic toe walking (ITW) is persistent forefoot walking without identifiable neurological or orthopedic causes. Emerging evidence suggests sensory–motor contributions, yet performance-based evaluations are limited. This study aimed to compare sensory integration and praxis in children with ITW and typically developing (TD) peers. **Methods**: This case–control study included 60 children (4–8 years 11 months): 30 with ITW and 30 TD. Diagnosis was confirmed using the Idiopathic Toe Walking Tool–Turkish Version. Sensory integration and praxis were assessed with the Sensory Integration and Praxis Tests (SIPTs). Group differences were analyzed using univariate analyses with Bonferroni correction, and dysfunction patterns were identified. **Results**: Children with ITW showed significantly poorer performance on several SIPT subtests, including Manual Form Perception, Graphesthesia, Postural Praxis, Praxis on Verbal Command, Oral Praxis, Bilateral Motor Coordination, and Standing and Walking Balance ($p < 0.001$). Figure–Ground perception also differed ($p = 0.003$), while kinesthesia and postrotary nystagmus did not. Somatodyspraxia was identified in 86.7% of the ITW group; other patterns were less frequent. No TD child met dysfunction criteria. **Conclusions**: Children with ITW exhibit sensory integration and praxis impairments, supporting a sensory–motor basis and the need for performance-based assessment.

Keywords: idiopathic toe walking; sensory integration; praxis

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1. Introduction

Idiopathic toe walking (ITW) is most commonly defined as a gait pattern in which children continue to walk on their forefoot (e.g., toes) beyond the age at which a consistent heel–toe gait is typically expected, despite the absence of neurological, orthopedic, or developmental conditions known to cause toe walking. Accordingly, ITW is considered a diagnosis of exclusion, made only after alternative etiologies—such as cerebral palsy, neuromuscular disease, congenital contractures, or neurodevelopmental disorders—have been ruled out [1–3]. Although toe walking may transiently occur during typical early motor development, most children achieve heel strike by approximately 18 months to two years of age, and persistence beyond this window warrants clinical attention [3–5]. Prevalence

estimates vary substantially across studies, ranging from approximately 5% in population-based cohorts to 24% in broader pediatric samples, suggesting that ITW is a relatively common presentation among otherwise healthy children [3,6,7]. Longitudinal data further indicate that, while many children spontaneously normalize their gait, a subset continues to toe-walk into later childhood. In one large cohort, 79% of children who had ever toe-walked adopted a typical gait by age 10 without intervention [6]. However, persistent ITW has been associated with reduced ankle dorsiflexion, increased stiffness, or contracture development, suggesting potential musculoskeletal implications for those who do not resolve naturally [1,7]. Together, these findings characterize ITW as a heterogeneous condition that may spontaneously resolve in some children but persist or become functionally relevant in others, underscoring the importance of careful clinical evaluation and monitoring.

Beyond gait-related characteristics, accumulating evidence suggests that children with ITW may differ from their typically developing peers across several neuromotor, developmental, and musculoskeletal domains. Preschool-aged children with ITW have been found to demonstrate lower psychomotor performance, reduced verbal and non-verbal developmental scores, and delays in neuropsychological maturity, pointing to broader neuromaturational vulnerabilities [8]. Musculoskeletal assessments commonly reveal reduced ankle dorsiflexion, localized or generalized joint stiffness, and limited range of motion across additional joints, with some children exhibiting a pattern of widespread hypomobility [7]. Neuropsychiatric profiles also appear distinct in this population, with elevated rates of motor coordination difficulties, executive function challenges, perceptual differences, language delays, social difficulties, and emotional–behavioral symptoms [9]. Complementing these findings, research has documented motor control impairments—including reduced muscle strength, impaired coordination, diminished postural stability, and altered proprioceptive responses—suggesting that neuromotor and sensory–motor integration factors may contribute to the persistence of toe walking [10,11]. Collectively, these findings reinforce the conceptualization of ITW as a multifactorial presentation involving interactions among biomechanical, neuromotor, and developmental systems.

In addition to these broader developmental and motor characteristics, sensory processing differences have also been documented in some children with ITW. Evidence from systematic reviews indicates that while a subset of children exhibit sensory modulation difficulties—including atypical tactile, proprioceptive, or vestibular responsiveness—others do not show marked sensory deviations [12]. On the other hand, more focused investigations have identified altered vibration perception thresholds, atypical quadrant scores on sensory questionnaires, and differences in a few subtests of the Sensory Integration and Praxis Test (SIPT) [13]. The early literature proposed associations between toe walking and sensory modulation challenges, such as vestibular under-responsiveness, tactile defensiveness, and sensory-seeking behaviors. However, findings have been inconsistent and often limited by methodological constraints [14]. Importantly, despite growing recognition of the potential sensory–motor components of ITW, existing studies have relied predominantly on caregiver-report measures or on isolated sensory-perception subtests. To date, a comprehensive performance-based assessment of sensory integration and praxis—examining how children process, integrate, and act on sensory information—has not been described in the ITW literature. This gap underscores the need for studies that systematically evaluate sensory perception alongside balance, coordination, and praxis to clarify the sensory–motor mechanisms that may contribute to persistent toe walking.

Therefore, the present study aims to comprehensively assess sensory integration and praxis skills in a group of children with idiopathic toe walking, providing a more complete understanding of the sensory–motor foundations of this condition.

2. Methods

2.1. Design

This study employed an observational, analytical, case–control design comparing a clinical group of children diagnosed with ITW and an age-matched group of typically developing children without a history of toe walking or sensory integration difficulties. Sensory integration and praxis functions were evaluated in both groups using the Sensory Integration and Praxis Test (SIPT) [15], and test outcomes were analyzed to compare group-level performance and identify patterns of sensory integration difficulty within the assessed sample.

2.2. Participants

A total of 60 children participated in the study. Children referred to the gait analysis laboratory of the Pediatric Orthopedics Department at a state university in Istanbul with a clinical suspicion of ITW were screened for eligibility. Initially, 34 children were referred by physicians with a preliminary diagnosis of ITW. All referred children subsequently underwent an additional clinical evaluation by the research team, and the diagnosis was confirmed using the Idiopathic Toe Walking Tool–Turkish Version [2]. Four children were excluded because previous psychiatric consultations and related clinical records indicated the presence of certain findings associated with autism spectrum disorder, which did not meet the criteria for idiopathic toe walking according to the Toe Walking Tool. Consequently, the final ITW group consisted of 30 children with confirmed idiopathic toe walking.

Children in the ITW group had no history of occupational or physical therapy and no prior diagnoses related to sensory integration or praxis difficulties. Inclusion criteria for the ITW group were: (1) a diagnosis of idiopathic toe walking established by a qualified clinician and confirmed using the Idiopathic Toe Walking Tool, (2) an age between 4 years 0 months and 8 years 11 months, corresponding to the age range specified for the Sensory Integration and Praxis Tests (SIPTs), and (3) the absence of neurological, orthopedic, or genetic conditions known to cause toe walking. The ITW group was established first, and the age and sex distributions of the eligible children were subsequently used as a reference when recruiting the control group.

The control group included 30 typically developing (TD) children with no history of toe walking or known neurological, orthopedic, developmental, or sensory integration disorders. Control participants were recruited from five primary schools in Istanbul, which also included kindergarten classes within the same school campuses, following meetings with school administrators and classroom teachers. Information about the study was communicated to parents through classroom teachers, who facilitated the dissemination of study information but were not involved in selecting participants. Children whose families voluntarily expressed interest in participating were subsequently screened for eligibility according to predefined inclusion and exclusion criteria. During control group recruitment, efforts were made to select children whose ages were as close as possible to those of the children already included in the ITW group, with the aim of achieving comparable age distributions between the groups. Sex distribution was also taken into consideration, although formal individual one-to-one matching was not performed.

The rationale for selecting typically developing children without known or parent-reported sensory integration concerns was aligned with the primary objective of the study. Specifically, the study aimed to characterize sensory integration and praxis performance in children with ITW who had no previous diagnosis of sensory integration or praxis difficulties and had not received occupational or physical therapy. Thus, the control group was intended to provide a comparison with typically developing peers without previously

identified sensory integration concerns, rather than to establish equivalence across all sensory–motor characteristics.

A total of 42 children were initially screened for participation in the control group. Eight children were excluded because of a history of occupational therapy intervention. During parent interviews, an additional four children were excluded because of suspected sensory integration difficulties, including concerns such as frequent falling and increased sensitivity to auditory or tactile input. Inclusion criteria for the control group included the absence of parent-reported sensory integration concerns, an age comparable to that of the children included in the ITW group, no history of persistent toe walking, and no known neurological, orthopedic, or developmental diagnoses.

All enrolled participants completed the assessment protocol and were included in the final analyses, with no missing data for the analyzed variables. The study was approved by the Non-Interventional Research Ethics Committee of Üsküdar University (Approval No: 61351342/2020-1047; 27 March 2025). Written informed consent was obtained from the parents or legal guardians of all participating children before inclusion in the study.

2.3. Sample Size Calculation

A priori power analysis was conducted using G*Power 3.1 to estimate the required sample size for detecting group differences between children with idiopathic toe walking and typically developing children. Based on earlier pilot testing conducted as a different study [16], assuming a medium effect size (f = 0.25), an alpha level of 0.05, and a desired statistical power of 0.80 for a two-group comparison, the analysis indicated that a minimum total sample size of 52 participants was required. The final sample size of 60 children (30 per group) exceeded this threshold, indicating adequate power to detect meaningful group differences.

2.4. Measures

2.4.1. The Toe Walking Tool (TWT)-Turkish Version

The TWT was used to confirm the diagnosis of idiopathic toe walking in the clinical group. The TWT is a structured clinical screening instrument originally developed to assist clinicians in differentiating idiopathic toe walking from toe walking associated with neurological, orthopedic, or developmental conditions. The tool consists of 21 dichotomous (yes/no) items organized across three sections: medical history (5 items), birth and developmental history (4 items), and clinical examination findings (12 items). A positive response to any item indicates the need for further medical evaluation, whereas the absence of positive findings supports a classification of idiopathic toe walking [17]. The Turkish version of the TWT was adapted and psychometrically evaluated by Tanrıverdi et al. (2021) [2]. The Turkish adaptation demonstrated acceptable reliability and validity for use in children with idiopathic toe walking, with good test–retest reliability (ICC = 0.674) and internal consistency coefficients (Cronbach's alpha) ranging from 0.476 to 0.823 across sections. These findings support the use of the TWT-Turkish Version as a reliable and valid clinical tool for confirming idiopathic toe walking in Turkish children [2].

2.4.2. Sensory Integration and Praxis Test (SIPT)

Sensory integration and praxis functions were assessed using the SIPT, a comprehensive performance-based assessment developed by Ayres (1989) to evaluate sensory integration functioning in children aged 4 to 8.11 years [15]. The SIPT consists of a standardized battery of 17 independent subtests designed to assess sensory perception, balance, bilateral coordination, praxis, and the integration of sensory input across multiple domains. The Design Copying test was not administered due to the unavailability of the required testing

materials. Table 1 presents the subtest names, standard name abbreviations, and a brief description of the subtest. Raw scores from each subtest are converted to standardized z scores using a computerized scoring system, with values ranging from −3.0 to +3.0. Scores below −1.0 indicate performance below age expectations, scores between −1.0 and +1.0 indicate performance within the expected range, and scores above +1.0 indicate performance above age expectations. The SIPT is considered the gold standard for assessing sensory integration and praxis and is typically administered to children with mild disabilities, including motor coordination difficulties, dyspraxia, learning disabilities, attention problems, and sensory modulation challenges. The subtests are organized into four overlapping domains: (a) visual form and space perception and visuomotor skills; (b) tactile, kinesthetic, and vestibular processing; (c) praxis; and (d) bilateral integration and sequencing. Psychometric evaluation of the SIPT demonstrates strong reliability, with adequate interrater reliability among certified examiners and satisfactory test–retest reliability for 13 of the 17 subtests (Pearson correlations ranging from 0.69 to 0.93). Although four subtests—postrotary nystagmus, kinesthesia, location of tactile stimulation, and figure–ground perception—showed lower test–retest reliability, overall evidence supports the reliability and validity of the SIPT as documented in the test manual [15,18]. Interpretation of SIPT results is based on patterns of performance across subtests rather than isolated test scores. Administration of the SIPT required approximately two hours for each child. To minimize fatigue and support optimal performance, a 30–40 min break was provided midway through the assessment to allow children time for rest and personal needs.

Table 1. Sensory Integration and Praxis Tests (SIPTs): subtests, abbreviations, and descriptions (Ayres, 1989) [15].

Abbreviation	Full Test Name	Primary Ability Assessed/Description
SV	Space Visualization	Assesses motor-free visual–spatial perception and the ability to mentally manipulate objects in space, including midline crossing tendencies and preferred hand use.
FG	Figure–Ground Perception	Measures the ability to perceive and identify a visual figure embedded within a competing background without motor involvement.
SWB	Standing and Walking Balance	Evaluates static and dynamic balance with eyes open and closed, reflecting vestibular and proprioceptive system functioning.
DC	Design Copying	Assesses visual–motor integration, spatial organization, and constructional approach during copying of geometric designs, including directionality, reversals, and segmentation.
PPr	Postural Praxis	Measures the ability to imitate body postures based on tactile and proprioceptive awareness, reflecting whole-body motor planning.
BMC	Bilateral Motor Coordination	Evaluates the ability to coordinate both sides of the body in smooth, rhythmical, and sequenced movements relying on vestibular and proprioceptive input.
PrVC	Praxis on Verbal Command	Assesses motor planning based solely on verbal instructions without a visual model, requiring translation of language into action.
CPr	Constructional Praxis	Measures the ability to plan and execute three-dimensional constructions using blocks, reflecting spatial organization and praxis.
PRN	Postrotary Nystagmus	Assesses vestibular system functioning by measuring duration of postrotary nystagmus following rotation, reflecting central vestibular processing.

Table 1. *Cont.*

Abbreviation	Full Test Name	Primary Ability Assessed/Description
MAc	Motor Accuracy	Evaluates visuomotor coordination, fine motor precision, and midline crossing during a tracing task.
SPr	Sequencing Praxis	Measures the ability to imitate, sequence, and coordinate a series of hand and arm movements, relying on tactile–proprioceptive input and memory.
OPr	Oral Praxis	Assesses motor planning of oral structures (tongue, lips, jaw) based on tactile and proprioceptive feedback without visual guidance.
MFP	Manual Form Perception	Measures tactile–kinesthetic perception and stereognosis by identifying geometric shapes through touch without visual input.
KIN	Kinesthesia	Assesses awareness of limb position and movement based on proprioceptive input, reflecting position sense.
FI	Finger Identification	Measures tactile discrimination by identifying which fingers are touched without visual input.
GRA	Graphesthesia	Assesses tactile perception and spatial processing by identifying shapes drawn on the hand without vision.
LTS	Localization of Tactile Stimuli	Measures accuracy of localizing light tactile input and sensitivity to touch, often associated with sensory modulation.

2.5. Procedures

All assessments were conducted between March and August 2025 in two private occupational therapy clinics in Istanbul. Sensory integration and praxis were evaluated using the SIPT by two independent, blinded occupational therapists certified in SIPT administration. Each child completed the assessment in a standardized testing environment following the procedures outlined in the SIPT manual. Assessments were administered individually, and children were provided with rest breaks as needed to minimize fatigue and ensure optimal performance. Standardized administration and scoring procedures were strictly followed to ensure assessment fidelity. All participants completed the evaluation protocol, and no modifications to the assessment procedures were required.

Several procedures were implemented to minimize potential sources of bias inherent to the case–control design. Selection bias was reduced through the use of clearly defined inclusion and exclusion criteria for both groups. The control group was selected to be comparable to the ITW group in terms of age and gender distribution. To reduce diagnostic misclassification, idiopathic toe walking was confirmed using the Toe Walking Tool–Turkish Version in addition to clinical evaluation. Measurement bias was minimized by administering all assessments in standardized testing environments according to SIPT manual procedures, and evaluations were conducted by two independent occupational therapists certified in SIPT administration who were blinded to the study aims and group formulas. Rest breaks were provided as needed to reduce fatigue-related performance effects. Furthermore, Bonferroni correction was applied during statistical analyzes to control for Type I error associated with multiple comparisons.

2.6. Data Analysis

Prior to hypothesis testing, the dataset was screened for completeness, outliers, and conformity with statistical assumptions. Normality of the outcome measures was evaluated using skewness and kurtosis values, Shapiro–Wilk tests, and visual inspection of histograms, Q–Q plots, and residual distributions. Skewness and kurtosis values ranged between −2 and +2, indicating an acceptable level of distribution [19,20]. Homogeneity of variances

and covariance matrices was examined using Levene's test and Box's M test, respectively. Multivariate outliers were assessed using Mahalanobis distance values prior to conducting MANOVA analyses. Descriptive statistics (means, standard deviations, and frequencies) were calculated to summarize demographic and sensory variables. Group differences in age were examined using an independent-samples *t*-test, whereas differences in gender distribution between TD and ITW groups were evaluated using Pearson's chi-square test. Statistical analyses were performed using IBM SPSS Statistics for Windows, Version 22.0 (IBM Corp., Armonk, NY, USA).

To assess overall group differences across the 16 sensory measures, a one-way multivariate analysis of variance (MANOVA) was conducted with group (TD vs. ITW) as the independent variable and all sensory scores entered as dependent variables. Given the significant multivariate effect, follow-up univariate analyses of variance (ANOVAs) were performed for each sensory outcome to identify specific variables contributing to group differences. Effect sizes for univariate analyses were reported using partial eta squared ($P\eta^2$).

Because multiple comparisons were performed across 16 sensory variables, a Bonferroni-adjusted significance level was applied to control for Type I error. The corrected threshold for statistical significance was set at $\alpha = 0.0031$ (0.05/16). Both unadjusted *p*-values and interpretations based on the corrected α level were reported. All tests were two-tailed, and results were considered statistically significant when $p < 0.05$, unless otherwise specified by Bonferroni adjustment.

Group-specific patterns of sensory integration dysfunction were identified through analysis of primary SIPT scores [21], and the distribution of children across identified patterns was reported as percentages.

3. Results

A one-way MANOVA revealed a significant multivariate effect of group (TD vs. ITW) on the combined SIPT variables: Wilks' $\Lambda = 0.171$, $F(16, 43) = 13.01$, $p < 0.001$, $\eta^2p = 0.829$. Follow-up univariate ANOVAs were subsequently conducted to determine which sensory variables contributed to the overall multivariate effect. Group comparisons of the 16 SIPT subtest z scores are presented.

3.1. Participant Characteristics

A total of 60 children participated in the study, including 30 TD children and 30 children with ITW. Table 2 presents the demographic characteristics of the sample. The mean age of the TD group was 79.13 months (SD = 16.43), while the ITW group had a mean age of 79.73 months (SD = 16.15). Both groups included children across a similar age range, with 10 children (33.3%) aged 4–5 years and 20 children (66.7%) aged 6 years or older in each group. An independent-samples *t*-test indicated no statistically significant difference in mean age between the groups: $t(58) = -0.14$, $p > 0.05$.

Table 2. Participant characteristics by group.

Variables	TD Group (n = 30)	ITW Group (n = 30)	Total (n = 60)	*p*
Age (months), Mean ± SD	79.13 ± 16.43	79.73 ± 16.15	79.43 ± 16.15	0.887 [a]
Gender, n (%)				0.739 [b]

Table 2. *Cont*.

Variables	TD Group (n = 30)	ITW Group (n = 30)	Total (n = 60)	*p*
Female	5 (16.7%)	6 (20.0%)	11 (18.3%)	
Male	25 (83.3%)	24 (80.0%)	49 (81.7%)	

[a] Independent-samples *t*-test. [b] Pearson Chi-square test ($\chi^2(1) = 0.111$, $p = 0.739$). **Note.** TD: typically developing; ITW: idiopathic toe walking.

Similarly, the sex distribution did not differ significantly between groups. In the TD group, 16.7% of participants were female and 83.3% were male, whereas in the ITW group, 20.0% were female and 80.0% were male. A Pearson chi-square test indicated no significant association between sex and group membership: $\chi^2(1) = 0.111$, $p > 0.05$. Overall, the TD and ITW groups were comparable in terms of mean age and sex distribution.

3.2. Group Differences in the SIPT Subtest

Group comparisons of the 16 SIPT subtest z scores are presented in Table 3. After applying the Bonferroni-adjusted significance threshold ($\alpha = 0.0031$), several significant differences emerged between the TD and ITW group.

Table 3. Comparison of sensory measures between typically developing children and children with idiopathic toe walking.

Variables	TD Group (Mean ± SD)	ITW Group (Mean ± SD)	F	*p*	η^2p
SV	0.13 ± 0.92	−0 0.40 ± 1.15	3.90	0.053	0.063
FG	0.00 ± 0.81	−0.64 ± 0.80	9.65	0.003 *	0.143
MFP	−0.02 ± 0.88	−1.06 ± 1.20	14.65	<0.001 *	0.200
KIN	0.04 ± 0.63	−0.58 ± 1.11	6.99	0.011	0.108
FI	0.00 ± 0.65	−0.32 ± 1.04	2.11	0.152	0.035
GRA	−0.28 ± 0.45	−1.55 ± 0.78	60.02	<0.001 *	0.509
LTS	−0.05 ± 0.91	−0.49 ± 1.28	2.32	0.134	0.038
PRVC	−0.12 ± 0.52	−0.85 ± 0.90	14.44	<0.001 *	0.199
CPr	0.45 ± 0.73	0.05 ± 1.12	2.65	0.109	0.044
PPr	−0.24 ± 0.57	−1.87 ± 0.70	98.25	<0.001 *	0.629
OPr	−0.45 ± 0.48	−1.94 ± 0.95	58.92	<0.001 *	0.504
SPR	−0.24 ± 0.84	−0.94 ± 1.03	8.38	0.005	0.126
BMC	−0.16 ± 0.66	−1.49 ± 0.86	45.49	<0.001 *	0.440
SWB	−0.60 ± 0.53	−1.70 ± 0.68	48.39	<0.001 *	0.455
MAC	0.60 ± 0.81	0.17 ± 1.36	2.20	0.143	0.037
PRN	−0.62 ± 0.84	−0.77 ± 1.29	0.27	0.607	0.005

Note. SIPT scores are presented as standardized z scores. Degrees of freedom for all F statistics were (1, 58). Bonferroni-adjusted significance level was set at $\alpha = 0.0031$. * $p < 0.0031$ indicates significance after Bonferroni correction. TD: typically developing; ITW: idiopathic toe walking.

Children with ITW demonstrated significantly lower performance than TD children on the following measures: MFP, $F(1,58) = 14.65$, $p < 0.001$, P$\eta^2 = 0.200$; GRA, $F(1,58) = 60.02$, $p < 0.001$, P$\eta^2 = 0.509$; PRVC, $F(1,58) = 14.44$, $p < 0.001$, P$\eta^2 = 0.199$; PPr, $F(1,58) = 98.25$,

$p < 0.001$, $P\eta^2 = 0.629$; OPr, $F(1,58) = 58.92$, $p < 0.001$, $P\eta^2 = 0.504$; BMC, $F(1,58) = 45.49$, $p < 0.001$, $P\eta^2 = 0.440$; and SWB, $F(1,58) = 48.39$, $p < 0.001$, $P\eta^2 = 0.455$. These effects ranged from medium to large, indicating robust group differences across these sensory–motor domains. Additionally, the FG measure reached the Bonferroni-adjusted significance level: $F(1,58) = 9.65$, $p = 0.003$, $P\eta^2 = 0.143$.

For the remaining SIPT variables (SV, KIN, FI, LTS, CPR, SPr, MAC, PRN), no statistically significant group differences were detected after adjustment for multiple comparisons ($p > 0.0031$). Although some variables demonstrated nominal significance at the unadjusted $\alpha = 0.05$ level (e.g., KIN, SPr), these differences did not survive correction for multiple testing.

In summary, children with ITW showed significantly poorer performance across multiple SIPT subdomains, particularly those with the largest effect sizes (PPr, OPr, GRA, SWB, BMC), even after applying conservative corrections for multiple comparisons.

3.3. Sensory Integration Dysfunction Patterns Based on SIPT z Scores

In the typically developing group (n = 30), analysis of SIPT z scores revealed that a subset of children performed below −1.0 on several subtests. The highest proportion of low scores was observed in PRN (20.0%) and BMC (16.7%). Lower-than-expected performance was also noted in FG (13.3%), MFP, LTS, OPR, SPR, and SWB (each 10.0%). Smaller proportions of children scored below −1.0 on KIN and MAC (each 6.7%), as well as SV, GRA, and CPR (each 3.3%), while no scores below −1.0 were observed for FI or PRVC. Although performance variability and isolated difficulties were observed across different SIPT domains, SIPT score patterns did not meet the criteria for classification of any sensory integration dysfunction pattern in this group.

Table 4 lists the subtests and criteria for each of the SIPT patterns. Based on SIPT score patterns, multiple sensory integration dysfunction profiles were identified within the ITW group (see Table 5). The most prevalent pattern was somatodyspraxia, with 26 children (86.7%) meeting the criteria for this profile. Visuodyspraxia was observed in 5 children (16.7%), while vestibular and bilateral integration deficits were identified in 2 children (6.7%). Additionally, poor sensory perception was present in 2 children (6.7%). As shown in Table 5, some children met criteria for more than one sensory integration dysfunction pattern, reflecting overlapping sensory–motor characteristics within the sample (Schaaf & Mailloux, 2015 [21]).

Table 4. Subtests and criteria for each of the SIPT patterns (Schaaf & Mailloux, 2015 [21]).

Sensory Integration Pattern	SIPT Subtests Expected to Show Low Scores	Key Clinical Interpretation
Poor Sensory Perception	FI, LTS, GRA, MFP, KIN, PRN, SV, FG	Reduced perceptual discrimination across multiple sensory systems (tactile, proprioceptive, vestibular, and visual).
Somatodyspraxia (Tactile-Based Praxis Deficit)	FI, LTS, GRA, MFP + PPr, OPr, SPr, PrVC	Concurrent impairment in tactile perception and praxis, indicating difficulty using somatosensory input for motor planning.
Visuodyspraxia (Visual-Based Praxis Deficit)	SV, FG + DC, CPr, MAc	Co-occurring deficits in visual perception and visual–motor or visual praxis abilities.

Table 4. *Cont*.

Sensory Integration Pattern	SIPT Subtests Expected to Show Low Scores	Key Clinical Interpretation
Vestibular and Bilateral Integration Dysfunction	PRN, SWB, BMC, SPr, OPr	Weakness in balance, bilateral coordination, sequencing, and postural–ocular control associated with vestibular processing.
Praxis on Verbal Command Deficit	PrVC (selectively low)	Difficulty translating verbal instructions into organized motor actions; performance typically improves with visual modeling.

Table 5. Common patterns of sensory integration dysfunction based on SIPT scores.

Common Patterns of Sensory Integration Dysfunction (SIPT)	Number of Participants Meeting the Criteria (n)		% of Participants Meeting the Criteria (%)	
	TD	ITW	TD	ITW
Somatodyspraxia	0	26	0	86.7
Visuodyspraxia	0	5	0	16.7
Vestibular and Bilateral Integration Deficits	0	2	0	6.7
Poor Sensory Perception	0	2	0	6.7

Note. Some participants met criteria for more than one sensory integration dysfunction pattern; therefore, percentages do not total 100%. TD: typically developing; ITW: idiopathic toe walking.

4. Discussion

The present study aimed to comprehensively examine clinical patterns of sensory integration and praxis functioning in children with ITW who had no known prior sensory integration dysfunction, using a standardized, performance-based assessment. The findings demonstrate that, despite comparable demographic characteristics between groups, children with ITW exhibited significantly poorer performance than typically developing peers across multiple SIPT subdomains, particularly those related to praxis, tactile perception, balance, and bilateral motor coordination. These group-level differences were accompanied by a high prevalence of identifiable sensory integration dysfunction patterns within the ITW group, most notably somatodyspraxia. In contrast, no participant in the typically developing group met criteria for a sensory integration dysfunction pattern despite isolated subtest-level variability. Together, these results suggest that ITW is associated not only with quantitative reductions in sensory–motor performance but also with qualitatively distinct patterns of sensory integration dysfunction, supporting the conceptualization of ITW as a heterogeneous condition with meaningful sensory–motor underpinnings that may impact functional performance.

Children with ITW demonstrated poorer performance on the GRA and MFP subtests of the SIPT, indicating difficulties in higher-order tactile perception and discrimination. Both subtests require accurate interpretation of complex spatial and symbolic tactile input and are considered reflective of cortical-level somatosensory processing rather than basic tactile detection [15,22]. Notably, these SIPT subtests assess tactile perception primarily through hand and upper-extremity input [15], distinguishing the present findings from much of the existing ITW literature, which has predominantly examined tactile processing at the plantar surface of the foot. The identification of tactile perceptual difficulties through upper-limb-based assessment

suggests that tactile processing challenges in children with ITW may not be limited to the lower extremities but may reflect more generalized somatosensory integration differences. This interpretation is consistent with earlier SIPT-based work, such as the case series by Len et al. (2013), which similarly reported tactile perception in children with ITW, supporting the notion of whole-body tactile perceptual involvement rather than isolated foot-specific deficits [23]. Previous research using standardized or quantitative tactile assessments has identified altered vibration perception thresholds at the hallux, diminished plantar tactile sensitivity, and tactile hyposensitivity in subsets of children with ITW, pointing to atypical tactile perceptual processing at the lower extremities [12,24–26]. Feasibility studies employing two-point discrimination paradigms have further demonstrated altered tactile discrimination responses and associated neural processing in children with ITW, implicating central somatosensory integration mechanisms [27]. These findings further suggest that, in a subset of children with ITW, tactile perceptual processing may be less efficient, potentially limiting the quality of somatosensory information available for body schema formation and motor planning [22,27–29].

Within a broader theoretical framework, the Neuronal Group Selection Theory proposes that motor behaviors such as walking emerge through experience-dependent selection of neuronal groups shaped by the effectiveness of sensorimotor input [30]. From this perspective, inefficient processing of tactile input—whether arising from the hands, feet, or broader bodily surfaces—may reduce the quality of sensory information supporting postural control and motor planning, thereby influencing gait pattern formation, stability, and locomotor plasticity and potentially contributing to the persistence of non-typical gait patterns such as toe walking [30–33].

In contrast, no group differences were detected on the KIN subtest of the SIPT, which evaluates proprioceptive processing; this result aligns with prior studies suggesting that proprioceptive and kinesthetic assessments do not reliably distinguish children with ITW from their typically developing counterparts, further highlighting the variability of somatosensory outcomes in this demographic [12,17]. Moreover, consistent with our findings, Len et al. (2013) reported that none of the children with ITW participating in their study demonstrated atypical performance on the KIN subtest of the SIPT, with all children exhibiting typical kinesthetic functioning [23]. In our study, the absence of group differences on the SIPT KIN subtest may be explained by the fact that this assessment relies on upper extremity kinesthetic tasks [15], which may not be sensitive to ankle-specific proprioceptive differences characteristic of children with idiopathic toe walking, given established evidence that proprioceptive accuracy differs between arms and legs [34]. Notably, even studies that have directly assessed foot and ankle proprioception in children with ITW have not consistently identified clear proprioceptive deficits [12], indicating that the absence of group differences may not be attributable solely to the extremity being assessed but rather to broader limitations inherent in current proprioceptive measurement approaches. As outlined by Han et al. (2016), proprioception represents a complex construct influenced by task demands, testing conditions, and central processing, and commonly used assessment methods may lack the sensitivity and ecological validity required to detect subtle, functionally relevant proprioceptive alterations in this population [35].

Children with ITW demonstrated marked weaknesses across multiple praxis-related SIPT subtests, including PPr, OPr, PRVC, and BMC. Collectively, these findings indicate difficulties in the generation, organization, and execution of purposeful motor actions, which may adversely affect participation in activities of daily living [22]. Empirical evidence directly examining praxis abilities in children with ITW remains limited; however, findings from a small case series of five children assessed with the SIPT similarly reported praxis-related difficulties, supporting motor planning challenges in this population [23]. In

addition, although some studies have not directly evaluated praxis, investigations of motor coordination have consistently demonstrated reduced motor coordination in children with ITW. These findings may provide indirect support for the present results and suggest that children with ITW may experience difficulties coordinating body movements and planning actions required for daily activities [10]. From a sensory integration perspective, these praxis difficulties may be underpinned by inefficient somatosensory processing (particularly tactile-based impairments in body scheme formation), which has been well documented in the literature as a core mechanism contributing to deficits in motor planning and praxis performance in children [22,28].

Consistent with our findings, previous studies have reported balance impairments in children with ITW [12,23,36]. Using the SIPT, Williams et al. (2013) and Len et al. (2013) similarly identified lower performance on the balance subtest in children with ITW [23,36]. Complementary evidence from non-SIPT studies further supports these findings: De Oliveira et al. (2021) reported reduced balance, motor coordination, and muscle strength [10], while McHugh et al. (2021) demonstrated postural instability and increased difficulty maintaining balance under sensory-challenging conditions in children with ITW [11].

Although proprioceptive and vestibular inputs are traditionally emphasized in postural control, growing evidence indicates that tactile processing plays a central and dynamic role in balance regulation, particularly at the lower extremities [26]. Experimental studies demonstrate that tactile input from the lower leg and foot is flexibly upweighted during moments of increased postural demand, with tactile sensitivity dynamically modulated to support balance control when sensory feedback becomes behaviorally relevant [37]. Similarly, augmenting plantar tactile input has been shown to directly improve postural stability, whereas tactile cues from non-weight-bearing regions exert more indirect, cognitively mediated effects [38]. Together, these findings suggest that balance difficulties—such as those observed in ITW—may be more closely related to altered integration or utilization of plantar tactile information rather than to isolated proprioceptive or vestibular deficits.

Although visual perception has not previously been identified as impaired in children with ITW, the significant group difference observed on the SIPT FG subtest in the present study may reflect the larger sample size compared with earlier small case series that reported no visual perceptual difficulties [12,23]. Notably, despite some studies reporting broader developmental challenges in children with ITW [8,39], difficulties related explicitly to visual–motor skills have not been consistently documented, which is consistent with the current finding of no group differences between children with ITW and typically developing peers on visuomotor measures. Given evidence of elevated perceptual and executive difficulties in ITW populations and convergent findings from children with mild developmental difficulties showing impairments in perceptual organization and figure-ground processing, the reduced figure–ground perception seen in children with ITW should be interpreted as part of a broader neurodevelopmental profile rather than an isolated visual deficit [9,12,40].

Research examining vestibular function in children with idiopathic toe walking is also limited. While some studies have suggested reduced vestibular processing in this population [12], other work using the SIPT Postrotary Nystagmus Test (PRN) has reported typical vestibular performance in children with ITW [23]. Consistent with these findings, the present study did not identify significant group differences on the SIPT PRN subtest, indicating comparable vestibular processing between children with ITW and typically developing peers.

Analysis of SIPT score patterns indicated that somatodyspraxia was the most prevalent sensory integration dysfunction profile in the ITW group, with the majority of children meeting criteria for this pattern [21,22]. This result aligns with the SIPT-based case series

reported by Len et al. (2013), in which all five children with ITW demonstrated a somatodyspraxia profile, suggesting consistency across studies despite differences in sample size [23]. In addition to somatodyspraxia, the present study identified other sensory integration patterns, including visuodyspraxia and vestibular–bilateral integration deficits, albeit at lower frequencies, underscoring the heterogeneity of sensory integration profiles within the ITW population [12]. The presence of multiple, partially overlapping patterns indicates that ITW is not associated with a single, uniform sensory integration dysfunction, but rather reflects a range of sensory–motor organization challenges, with somatodyspraxia emerging as the most prominent and consistently reported profile. Furthermore, although some studies have documented broader developmental challenges in children with ITW [8,12,39], these converging sensory integration findings suggest that ITW may be better conceptualized as part of a broader neurodevelopmental variation rather than solely as an isolated gait abnormality.

The absence of distinct sensory integration patterns in typically developing children is consistent with SIPT-based factor and cluster analyses, which demonstrate that sensory integration abilities in this population are distributed along a normative continuum rather than forming discrete or clinically meaningful profiles [15,18,41]. In contrast, well-defined sensory integration and praxis patterns have been reliably identified in children with neurodevelopmental disorders, indicating that such patterns emerge preferentially in the context of atypical neurodevelopment [18,41,42]. Converging evidence further shows that sensory processing difficulties are substantially more prevalent and more systematically organized in neurodevelopmental conditions than in typical development, supporting the interpretation that the absence of a clear SIPT pattern in typically developing children reflects normative variability rather than a limitation of the assessment itself [43,44].

Several limitations of the present study should be acknowledged. First, although sensory integration and praxis were comprehensively assessed using a standardized performance-based measure, caregiver-report instruments targeting sensory modulation, such as the Sensory Processing Measure-2nd [45] or the Sensory Profile [46], were not included. Consequently, sensory modulation patterns and sensory responsivity in everyday contexts could not be fully characterized. This represents an important limitation, particularly given that previous studies have frequently examined sensory modulation differences in children with ITW using parent-report measures [12]. Second, the study did not directly examine the functional impact of sensory integration difficulties on daily participation or explore the relationships between sensory integration dysfunction patterns and biomechanical or gait characteristics. Such assessments could have provided additional insight into how sensory–motor differences relate to functional movement in children with ITW. Third, although the ITW and typically developing groups were comparable in age and sex distribution, equivalence across all clinical and developmental characteristics could not be established. In particular, the exclusion of children with parent-reported sensory integration concerns from the control group may have influenced the magnitude of the observed group differences. Additionally, voluntary participation and recruitment from different clinical and educational settings may have introduced selection bias, despite the use of predefined eligibility criteria and the absence of direct participant selection by teachers. Therefore, the findings should be interpreted in the context of the study's intended comparison between children with ITW who had no previous diagnosis of sensory integration or praxis difficulties and typically developing peers without previously identified sensory integration concerns, rather than as evidence of a causal relationship between ITW and sensory integration or praxis dysfunction. Finally, although praxis-related difficulties were identified, motor skill performance was not independently assessed using standardized motor measures. Including a direct evaluation of motor abilities may have enabled a more

detailed examination of the relationships among sensory integration, praxis, and motor performance in children with ITW.

Despite these limitations, the findings carry important clinical and research implications. Clinically, they highlight the value of incorporating comprehensive sensory–motor evaluations into the assessment of children with ITW, extending beyond gait analysis to include standardized measures of sensory integration, praxis, and motor coordination. Recognition of sensory integration dysfunction may inform more individualized intervention planning and support the integration of sensory-based strategies alongside conventional motor or orthopedic approaches. From a research perspective, future studies would benefit from multimethod, longitudinal designs that combine performance-based sensory assessments, caregiver-reported measures, functional participation outcomes, and objective analyses of gait and motor performance. Such approaches may help clarify the complex sensory–motor mechanisms underlying idiopathic toe walking and further elucidate whether observed sensory integration patterns represent contributing factors, developmental correlates, or adaptive features within a broader neurodevelopmental profile.

5. Conclusions

This study demonstrates that children with idiopathic toe walking display unique abnormalities in sensory integration and praxis when evaluated with a comprehensive, performance-based assessment. Compared with typically developing peers, children with ITW experienced difficulties across various SIPT domains, particularly tactile perception, praxis, balance, and bilateral motor coordination, and exhibited a high incidence of somatodyspraxia. These data indicate that ITW is not merely a biomechanical gait variant but a heterogeneous syndrome associated with significant abnormalities in sensory–motor organization. The results underscore the importance of standardized performance-based assessments in detecting higher-order sensory integration and praxis difficulties that may not be evident solely through caregiver-report measures. A more profound comprehension of sensory integration and praxis functioning in children with ITW may enhance targeted assessment methods and facilitate the creation of personalized intervention plans that address both motor performance and functional involvement.

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Glossary of Key Terms

Sensory integration	The processing and organization of sensory information to support adaptive responses and purposeful activity.
Praxis	The ability to conceive, plan, sequence, and carry out purposeful actions.
Somatodyspraxia	A pattern of difficulty with motor planning associated with reduced tactile and body-based sensory perception.
Visuodyspraxia	Difficulty with motor planning and constructional tasks associated with visual–perceptual processing.
Vestibular and bilateral integration dysfunction	A pattern of difficulty with balance, bilateral coordination, and sequencing associated with vestibular-related functions.
Poor sensory perception	A pattern of reduced sensory discrimination across one or more sensory modalities.

References

1. Bauer, J.P.; Sienko, S.; Davids, J.R. Idiopathic toe walking: An update on natural history, diagnosis, and treatment. *J. Am. Acad. Orthop. Surg.* **2022**, *30*, e1419–e1430. [CrossRef] [PubMed]
2. Tanrıverdi, M.; Tunç, B.; İşcan, A. Reliability and validity of the Toe Walking Tool in Turkish idiopathic toe walking children. *Haliç Üniversitesi Sağlık Bilim. Derg.* **2021**, *4*, 137–143. [CrossRef]
3. Üstün, C.; Menderes, D.; Özbudak, P.; Öncel, E.P.; Konuşkan, B. Children presenting with toe walking: When should concern arise? *Cukurova Med. J.* **2024**, *49*, 736–743. [CrossRef]
4. Caserta, A.; Reedman, S.; Morgan, P.; Williams, C.M. Physical activity and quality of life in children with idiopathic toe walking: A cross-sectional study. *BMC Pediatr.* **2022**, *22*, 544. [CrossRef] [PubMed]
5. Morozova, O.M.; Chang, T.F.; Brown, M.E. Toe walking: When do we need to worry? *Curr. Probl. Pediatr. Adolesc. Health Care* **2017**, *47*, 156–160. [CrossRef] [PubMed]
6. Engström, P.; Tedroff, K. Idiopathic toe-walking: Prevalence and natural history from birth to ten years of age. *J. Bone Jt. Surg. Am.* **2018**, *100*, 640–647. [CrossRef] [PubMed]
7. Engelbert, R.; Gorter, J.W.; Uiterwaal, C.; van de Putte, E.; Helders, P. Idiopathic toe-walking in children, adolescents and young adults: A matter of local or generalised stiffness? *BMC Musculoskelet. Disord.* **2011**, *12*, 61. [CrossRef] [PubMed]
8. Martín-Casas, P.; Ballestero-Pérez, R.; Meneses-Monroy, A.; Beneit-Montesinos, J.V.; Atín-Arratibel, M.A.; Portellano-Pérez, J.A. Neurodevelopment in preschool idiopathic toe-walkers. *Neurologia* **2017**, *32*, 446–454. [CrossRef] [PubMed]
9. Engström, P.; Van't Hooft, I.; Tedroff, K. Neuropsychiatric symptoms and problems among children with idiopathic toe-walking. *J. Pediatr. Orthop.* **2012**, *32*, 848–852. [CrossRef] [PubMed]
10. De Oliveira, V.; Arrebola, L.; De Oliveira, P.; Yi, L. Investigation of muscle strength, motor coordination and balance in children with idiopathic toe walking: A case-control study. *Dev. Neurorehabil.* **2021**, *24*, 540–546. [CrossRef] [PubMed]
11. McHugh, J.J.; Baxter, M.F.; Chang, P.F.; Mitchell, K. Idiopathic toe walking and postural instability: The next step. *Ann. Int. Occup. Ther.* **2021**, *4*, e109–e116. [CrossRef]
12. Donne, J.H.; Williams, C.M. Some children with idiopathic toe walking display sensory processing difficulties but not all: A systematic review. *Acta Paediatr.* **2023**, *112*, 1620–1632. [CrossRef] [PubMed]
13. Williams, C.M.; Tinley, P.; Curtin, M.; Wakefield, S.; Nielsen, S. Is idiopathic toe walking really idiopathic? The motor skills and sensory processing abilities associated with idiopathic toe walking gait. *J. Child Neurol.* **2014**, *29*, 71–78. [CrossRef] [PubMed]
14. Williams, C.M.; Tinley, P.; Curtin, M. Idiopathic toe walking and sensory processing dysfunction. *J. Foot Ankle Res.* **2010**, *3*, 16. [CrossRef] [PubMed]
15. Ayres, A.J. *Sensory Integration and Praxis Tests*; Western Psychological Services: Los Angeles, CA, USA, 1989.
16. May-Benson, T.A.; Balikci, A. Sensory integration patterns in children with idiopathic toe walking. *Am. J. Occup. Ther.* **2025**, *79*, S337. [CrossRef]

17. Williams, C.M.; Tinley, P.; Curtin, M. The Toe Walking Tool: A novel method for assessing idiopathic toe walking children. *Gait Posture* **2010**, *32*, 508–511. Erratum in *Gait Posture* **2011**, *34*, 442. https://doi.org/10.1016/j.gaitpost.2011.08.017. [CrossRef] [PubMed]
18. Mulligan, S. Patterns of sensory integration dysfunction: A confirmatory factor analysis. *Am. J. Occup. Ther.* **1998**, *52*, 819–828. [CrossRef]
19. Tabachnick, B.G.; Fidell, L.S. *Using Multivariate Statistics*, 6th ed.; Pearson: Boston, MA, USA, 2013.
20. George, D.; Mallery, P. *SPSS for Windows Step by Step: A Simple Guide and Reference*, 10th ed.; Pearson: Boston, MA, USA, 2010.
21. Schaaf, R.C.; Mailloux, Z. *Clinician's Guide for Implementing Ayres Sensory Integration®*; AOTA Press: Bethesda, MD, USA, 2015.
22. Bundy, A.C.; Lane, S.J. *Sensory Integration: Theory and Practice*, 3rd ed.; F.A. Davis Company: Philadelphia, PA, USA, 2020.
23. Len, A.Y.; Rao, S. Idiopathic toe walking and sensory processing dysfunction. *Pediatr. Phys. Ther.* **2012**, *24*, 378–379.
24. Onerge, K.; Sert, R.; Akalan, N.E.; Bilgili, F. Investigation of the Relationship between Plantar Pressure Behaviour and Plantar Surface Sensitivity in Children with Idiopathic Toe Walking. *Gait Posture* **2020**, *81*, 246. [CrossRef]
25. Williams, C.M.; Tinley, P.; Curtin, M.; Nielsen, S. Vibration perception thresholds in children with idiopathic toe walking gait. *J. Child Neurol.* **2012**, *27*, 1017–1021. [CrossRef] [PubMed]
26. Chu, V.; Girolami, G.L.; Grant-Beuttler, M. Assessing sensory processing differences in children with idiopathic toe walking: A pilot study. *Physiother. Theory Pract.* **2023**, *39*, 2314–2326. [CrossRef] [PubMed]
27. Donne, J.; Farrell, M.J.; Kolic, J.; Powell, J.; Fahey, M.; Williams, C. Two-point discrimination responses in children with idiopathic toe walking: A feasibility fMRI study. *Sci. Prog.* **2022**, *105*, 00368504221132141. [CrossRef] [PubMed]
28. Ayres, A.J.; Robbins, J. *Sensory Integration and the Child: Understanding Hidden Sensory Challenges*; Western Psychological Services: Los Angeles, CA, USA, 2005.
29. Lane, S.J.; Mailloux, Z.; Schoen, S.; Bundy, A.; May-Benson, T.A.; Parham, L.D.; Schaaf, R.C. Neural foundations of Ayres Sensory Integration®. *Brain Sci.* **2019**, *9*, 153. [CrossRef] [PubMed]
30. Hadders-Algra, M. The neuronal group selection theory: A framework to explain variation in normal motor development. *Dev. Med. Child Neurol.* **2000**, *42*, 566–572. [CrossRef] [PubMed]
31. Hospodar, C.M.; Adolph, K.E. The development of gait and mobility: Form and function in infant locomotion. *WIREs Cogn. Sci.* **2024**, *15*, e1677. [CrossRef] [PubMed]
32. Pluijter, N.; de Wit, L.P.W.; Bruijn, S.M.; Plaisier, M.A. Tactile pavement for guiding walking direction: An assessment of heading direction and gait stability. *Gait Posture* **2015**, *42*, 479–485. [CrossRef] [PubMed]
33. Teulier, C.; Lee, D.K.; Ulrich, B.D. Early Gait Development in Human Infants: Plasticity and Clinical Applications. *Dev. Psychobiol.* **2015**, *57*, 447–458. [CrossRef] [PubMed]
34. Paschalis, V.; Nikolaidis, M.G.; Giakas, G.; Jamurtas, A.Z.; Koutedakis, Y. Differences between arms and legs on position sense and joint reaction angle. *J. Strength Cond. Res.* **2009**, *23*, 1652–1655. [CrossRef] [PubMed]
35. Han, J.; Waddington, G.; Adams, R.; Anson, J.; Liu, Y. Assessing proprioception: A critical review of methods. *J. Sport Health Sci.* **2016**, *5*, 80–90. [CrossRef] [PubMed]
36. Williams, C.; Tinley, P.; Curtin, M.; Nielsen, S. The Motor Skills and Sensory Processing Abilities Associated with Idiopathic Toe Walking Gait. *J. Foot Ankle Res.* **2013**, *6*, O38. [CrossRef]
37. Wachsmann, F.D.; Fiehler, K.; Voudouris, D. Temporal modulation of tactile perception during balance control. *Sci. Rep.* **2025**, *15*, 17380. [CrossRef] [PubMed]
38. Azbell, J.; Park, J.; Chang, S.-H.; Engelen, M.P.K.G.; Park, H. Plantar or palmar tactile augmentation improves lateral postural balance with significant influence from cognitive load. *IEEE Trans. Neural Syst. Rehabil. Eng.* **2021**, *29*, 113–122. [CrossRef] [PubMed]
39. Shulman, L.H.; Sala, D.A.; Chu, M.L.Y.; McCaul, P.R.; Sandler, B.J. Developmental implications of idiopathic toe walking. *J. Pediatr.* **1997**, *130*, 541–546. [CrossRef] [PubMed]
40. Khamenehei, N.; Tokarskaya, L.V. Comparative visual perception patterns in autism spectrum disorder and mild intellectual disability: A cross-sectional study. *Consort. Psychiatr.* **2025**, *6*, CP15638. [CrossRef] [PubMed]
41. Mailloux, Z.; Mulligan, S.; Roley, S.S.; Blanche, E.; Cermak, S.; Coleman, G.G.; Lane, C.J. Verification and clarification of patterns of sensory integrative dysfunction. *Am. J. Occup. Ther.* **2011**, *65*, 143–151. [CrossRef] [PubMed]
42. Roley, S.S.; Mailloux, Z.; Parham, L.D.; Schaaf, R.C.; Lane, C.J.; Cermak, S. Sensory integration and praxis patterns in children with autism. *Am. J. Occup. Ther.* **2015**, *69*, 6901220010. [CrossRef] [PubMed]
43. Galiana-Simal, A.; Vela-Romero, M.; Romero-Vela, V.M.; Oliver-Tercero, N.; García-Olmo, V.; Benito-Castellanos, P.J.; Muñoz-Martínez, V.; Beato-Fernández, L. Sensory processing disorder: Key points of a frequent alteration in neurodevelopmental disorders. *Cogent Med.* **2020**, *7*, 1736829. [CrossRef]
44. Rodríguez-Armendáriz, E.; Vela-Romero, M.; Galiana, A. Sensory processing challenges in children with neurodevelopmental disorders and genetic conditions: An observational study. *NeuroSci* **2024**, *5*, 339–353. [CrossRef] [PubMed]

45. Parham, L.D.; Ecker, C.L.; Kuhaneck, H.; Henry, D.A.; Glennon, T.J. *Sensory Processing Measure*, 2nd ed.; Western Psychological Services: Torrance, CA, USA, 2021.
46. Dunn, W. *Sensory Profile 2: User's Manual*; Pearson: Bloomington, MN, USA, 2014.

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