Toddle Temporal-spatial Deviation Index: assessment of pediatric gait

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Abstract

This research aims to develop a gait index for use in the pediatric clinic as well as research, that quantifies gait deviation in 18-22 month-old children: the Toddler Temporal-spatial Deviation Index (Toddler TDI). 81 preterm children (≤ 32 weeks) with very-low-birth-weights (≤ 1500 g) and 42 full-term TD children aged 18-22 months, adjusted for prematurity, walked on a pressure-sensitive mat. Preterm children were administered the Bayley Scales of Infant Development—3rd Edition (BSID-III). Principle component analysis of TD children's temporal-spatial gait parameters quantified raw gait deviation from typical, normalized to an average (standard deviation) Toddler TDI score of 100(10), and calculated for all participants. The Toddler TDI was significantly lower for preterm versus TD children (86 vs. 100, $p = 0.003$), and lower in preterm children with < 85 vs. ≥ 85 BSID-III motor composite scores (66 vs. 89, $p = 0.004$). The Toddler TDI correlated with BSID-III gross motor ($r = 0.50$, $p < 0.001$) and not fine motor ($r = 0.19$, $p = 0.09$), suggesting sensitivity to gross motor development. The Toddler TDI, which by design plateaus at average (BSID-III gross motor 8-12), correlated more strongly with gross motor scores ≤ 8 ($r = 0.60$, $p < 0.001$). The Toddler TDI demonstrated sensitivity and specificity to gross motor function in very-low-birth-weight preterm children aged 18-22 months, and has potential as an easily-administered, revealing clinical gait metric.

Key words

Gait, motor development, toddler, assessment

Introduction

Children born preterm with very-low birth-weight are at risk for motor deficits ranging from mild discoordination to cerebral palsy. Cerebral palsy, the most common childhood disability,[1] occurs in approximately 15% of this population, a prevalence 50 times higher than in the general population.[2,3] Developmental coordination disorder, a milder motor impairment that interferes with daily-living activities,[4] affects an additional 40%.[5] Reliable early identification of motor deficits is essential for guiding treatment, which may prevent deformities, reduce the need for orthopedic surgery, and improve long-term motor function and quality of life. However, an inaccurate diagnosis is common before toddler age, with misdiagnoses of cerebral palsy highest before 24 months.[6–8]

Presently, identification of potential gross motor impairment in toddler-aged children is primarily based on clinical exam and motor milestone history. However, such assessments can yield poor specificity; in one study, half of the diagnoses of cerebral palsy made by the first birthday were retracted before the seventh.[7] Motor milestone assessments are made challenging by variability in parental report[9] and the wide age range of normal in milestone attainment—for example, independent walking occurs ~ 12 months, but 10% of apparently-healthy term-born children do not walk until 14.4 months or later.[10]

More structured assessments of gross motor function do exist for toddler-aged children. The Peabody Developmental Motor Scale-2 and Bayley Scales of Infant Development-3rd Edition (BSID-III) are in widespread clinical use.[11–13] However, both tests are long—the full BSID-III takes ~ 90 minutes for 18-22 month-olds,[12] and the Peabody is longer[13]—and expensive, with some clinics requiring a trained psychologist examiner. These limitations restrict the number of children clinics can administer neurodevelopmental assessments to, limiting

assessments to the highest-risk children. Components of these tests are also subjective, such as the BSID-III assessment of whether a child “runs with coordination.”[12] The gross motor subsection of the BSID-III could be administered separately, which would be quicker and cheaper, although no more quantitative or objective.

This research aims to develop a quantitative, objective single-score measure of toddler gross motor function in gait, designed for clinic as well as research use. The Toddler Temporal-spatial Deviation Index (Toddler TDI) is an index representing the deviation of a given toddler’s gait from typical, based on temporal-spatial gait parameters in typically-developing (TD) children aged 18-22 months. It increases with decreasing gait deviation, up to the average deviation of a TD child: scores are not designed to continue increasing for advanced walkers, thus the Toddler TDI is expected to plateau for average and better performance. The Toddler TDI is inspired by indices developed for 3D-motion-capture gait kinematics, the Gillette Gait Index and Gait Deviation Index, which are in widespread clinical use for the pediatric population with CP.[14,15] It is intended to identify and characterize gait impairments in children with suspected delay. We hypothesized that (i) Toddler TDI values would be significantly lower in preterm children performing below 1 SD of average (<85) on BSID-III composite motor compared to TD children, and (ii) that preterm children’s Toddler TDIs would correlate with their BSID-III gross motor subscores in children scoring up to and including average (≤ 88).

Method

Participants

81 very-low-birth-weight (≤ 1500 g) preterm (≤ 32 weeks gestational age) toddlers and 55 TD full-term (≥ 37 weeks) toddlers aged 18-22 months completed a single-visit gait assessment in this IRB-approved study, as described previously.[16,17] The age range of 18-22 months was chosen because evidence of motor impairments can be identified and a visit to the pediatrician is standard-of-care at this age, allowing the Toddler TDI to be administered clinically. Previously, we investigated the effect of walking experience in this cohort and found that it was not a major confound by this age; in addition, age is a more reliable measure than parental report of walking experience.[9,18] This age is also standard for follow-up evaluation with the BSID-III by the Neonatal Research Network.[19,20] 42 of the 55 TD toddlers met inclusion criteria of apparently-typical motor development, independent walking within 14 months of age[21], and no parental concerns about motor development. Preterm toddlers also received the BSID-III neurodevelopmental exam.

Assessment

A trained examiner performed the BSID-III as described previously.[16] Gait temporal-spatial parameters of children were calculated from 2-3 “best effort” walking trials recorded on a pressure-sensitive mat (GAITRite, CIR Systems, Inc., Sparta, NJ). Each walking trial used for analysis met three criteria: (i) at least four consecutive footfalls, (ii) at least one foot on the ground at any given time, and (iii) the child did not touch or carry anything. Age of independent walking was reported by parents. If a child was not yet walking independently, this was noted and the child’s data was included if they were able to walk with handheld assist. Gestational age was recorded from the medical record (preterm participants) or by parental report (TD participants).

Index formation

The Toddle TDI was built from temporal-spatial gait parameters of 42 TD toddlers, and may be calculated for any toddler by inputting his or her gait parameters into the supplementary spreadsheet included with this paper.

Candidate variables for the Toddle TDI were selected based on expected relevance to function based on prior studies[21–23] and previous findings in this cohort,[16] then reduced to a final set of variables based on acceptable Kaiser-Meyer-Olkin measures of sampling adequacy (MSA) for factoring, informed by differences in gait between preterm and TD children.[24] Step width and step length coefficient of variation (CoV), the only variables significantly different between preterm and TD toddlers, were included, as were velocity, step length, step length asymmetry, cycle time, single-limb support (SLS), and double-limb support (DLS), all of which are associated with motor function and routinely calculated in pediatric clinical gait analysis and toddler gait research.[21–23] To capture effects of variability, coefficients of variation (CoVs) for step width and SLS were included. Clinically-relevant but redundant parameters, such as stance phase, were excluded. We previously reported no correlation between gait parameters and height and weight in this cohort[18]; thus parameters were not normalized by toddler size.

Candidate variables consisted of velocity, cycle time, step width, step width CoV, step length, step length asymmetry, step length CoV, SLS, SLS CoV, and DLS.

Temporal-spatial gait parameters are highly interrelated. Principle component analysis with varimax rotation was therefore performed on the TD-toddler gait parameters not for dimension reduction purposes, but to decouple gait parameters into a set of independent components, or factors, similarly to the Gillette Gait Index.[14] Once defined, these independent factors can be calculated for any individual child, with each factor's value representing deviation from a TD-toddler-average counterpart; thus, the sum of the absolute values of an individual's factor scores is a measure of absolute deviation from average TD-toddler gait, and represents the raw Toddle TDI. We did not scale or weigh factors for percent variance explained (i.e. eigenvalue), because this could cause the index to be dominated by parameters (such as velocity) which are related to many other parameters (such as cycle time and step length), while under-weighting parameters (such as step width) which are relatively independent. In addition, factors which explain less absolute variation are not necessarily less clinically significant.

For ease of interpretation, the raw Toddle TDI was converted into a z-score with an average of 100 and standard deviation (SD) of 10 among the TD toddlers, similarly to the 3D-kinematic-based Gait Deviation Index.[15] Thus, a Toddle TDI of 90 represents 1 SD from typical gait, while a Toddle TDI of 75 represents 2.5 SDs from typical. It is possible for a child's Toddle TDI to exceed 100, if their gait is closer to average than a typical TD toddler's gait is likely to be. It is also possible for a child's Toddle TDI to fall below zero if the child's gait is >10 SDs from typical.

Index validation

Toddle TDI was calculated for all preterm toddlers, as well as the subsets of preterm toddlers with <85 versus ≥85 BSID-III motor composite scores. 85 was chosen as a cutoff because it is >1 SD from a typical score by design, and may represent up to 2 SD from a truly typical population.[12,20] Comparisons of means were made with one-way ANOVA and Tukey's test.

Pearson's correlations were performed between Toddler TDIs and BSID-III motor composite, fine motor, and gross motor scores, gestational age, and age of independent walking. Participants with missing BSID-III data were included in analyses for which data was available. Statistical analyses were computed with IBM SPSS statistics, version 23.

Results

Data from 42 TD participants was included in the calculation of the Toddler TDI. 55 TD participants attended the gait assessment: 5 were excluded due to parental concern about walking or motor development (one walked after 14 months); 7 because they walked after 14 months; and one due to observed excessive instability and apparent delayed gross motor resulting in a Toddler TDI more than 3 SDs from the mean.

Participant demographics are reported in **Table 1**. Preterm toddlers had a mean gestational age of 28 weeks 6 days (2 weeks 3 days), and completed the gait assessment aged 20.2(1.0) months adjusted for prematurity; TD toddlers were born at 39 weeks 5 days (1 week 2 days) and completed the gait assessment aged 19.9(1.2) months.

Figure 1 shows box plots of temporal-spatial gait parameters considered for the Toddler TDI. Step width, previously reported to be significantly different for TD and preterm toddlers,[16] showed the clearest trend of increasing values from TD, to preterm higher-scoring, to preterm lower-scoring toddlers. For this reason, step width was retained in the final set of variables comprising the Toddler TDI, despite an inadequate MSA. This is appropriate because the low MSA indicates only that step width does not adequately contribute to variation in TD-toddler gait; however, in preterm-toddler gait, step width is known to be more variable and therefore relevant. All other candidate variables with MSA <0.6 were serially excluded: step width CoV, step length, and step length asymmetry were dropped. The final set of variables used in calculating the Toddler TDI included velocity, cycle time, step width, step length CoV, SLS, SLS CoV, and DLS. Mean values of some temporal-spatial gait parameters were previously reported in this cohort.[16,17]

Figure 2 A reports mean Toddler TDI for preterm and TD children. Mean values were significantly lower for the preterm children, with mean (95% confidence interval) of 86 (80-93) compared to 100 (97-103) for TD children. The high Toddler TDI was 121 for both groups, and the low was 79 for TD and -48 for preterm toddlers.

Figure 2 B reports mean Toddler TDI for preterm children with BSID-III composite motor scores <85 versus ≥85, and for TD children. Two preterm participants were not administered the BSID-III. Tukey's test revealed significant differences between all three groups. Preterm toddlers with composite motor <85 had a significantly lower mean Toddler TDI of 66 (36-96) compared to both higher-scoring preterm children, with 89 (84-95), and TD children, with 100 (97-103). Additionally, the Toddler TDI of preterm children scoring ≥85 was significantly lower than that of TD children.

Figure 3 plots the Toddler TDI for preterm children in relation to their gross, fine, and composite BSID-III motor scores. The Toddler TDI correlated significantly with gross and composite motor scores for children scoring up to and including average (≤8, n=34) on BSID-III gross motor ($r=0.60$, $p<0.001$, and $r=0.35$, $p=0.040$, respectively). These children's Toddler TDIs did not

correlate significantly with fine motor score ($r=0.08$, $p=0.65$). Correlation of Toddle TDI and BSID-III gross motor for children scoring >8 ($n=45$) was $r=-0.04$, $p=0.79$.

The Toddle TDI did not correlate with gestational age ($r=0.22$, $p=0.18$) or age of independent walking ($r=0.01$, $p=0.96$) for TD children. For preterm children, Toddle TDI correlated with age of independent walking ($r=-0.36$, $p=0.003$) and demonstrated a trend with gestational age ($r=0.22$, $p=0.05$).

Sensitivity and specificity of Toddle TDI scores ≤ 80 to BSID-III gross motor scores ≤ 5 were 88% and 83%, respectively, resulting from 7 true positives, 12 false positives, 59 true negatives, and 1 false negative. Toddle TDIs ≤ 80 represent ≥ 2 SDs from typical, while gross motor scores ≤ 5 represent ≥ 1 SD from low-end typical. These cutoffs were chosen based on the large number of preterm children whose Toddle TDIs were ≥ 1 SD below typical, and the fact that no children had gross motor scores ≥ 2 SDs from typical.

Discussion

The Toddle TDI demonstrated clinical and construct validity. Preterm children had significantly lower mean Toddle TDI than TD toddlers. Furthermore, Toddle TDI was significantly lower for preterm toddlers who scored <85 BSID-III composite motor compared to those scoring ≥ 85 , and compared to TD toddlers, indicating that the Toddle TDI was sensitive to impairment as detected on the BSID-III. Mean Toddle TDI of preterm toddlers scoring ≥ 85 was significantly lower compared to TD toddlers, suggesting that the Toddle TDI is sensitive to gradations of impairment. The Toddle TDI exhibited a stronger correlation with gross motor ($r=0.60$, $p<0.001$) and composite motor ($r=0.35$, $p=0.040$) than any individual gait parameter previously reported,[16] supporting the construct validity and sensitivity of the Toddle TDI as a gross motor measure.

The scatterplot reveals that the relationship between the Toddle TDI and BSID-III appears stronger for more-affected children. This is due to the nature of the Toddle TDI, which assesses whether gait is typical or atypical: while 100 indicates average deviation, Toddle TDI scores >100 do not indicate better-than-average gait. By contrast, BSID-III scores increase with increasing ability, with 8-12 indicating average-range and >12 indicating better-than-average gross motor. Thus we hypothesized that the Toddle TDI would correlate with BSID-III for children with up-to-and-including average gross motor performance, while no correlation would be expected for children with better-than-typical performance. The correlation of the Toddle TDI to gross motor for children scoring ≤ 8 ($r=0.60$, $p<0.001$), compared to children scoring >8 ($r=-0.04$, $p=0.79$), confirmed our hypothesis.

Results support the hypotheses that Toddle TDI values would be significantly lower in preterm children scoring <85 composite motor compared to TD children, and that preterm children's Toddle TDIs would correlate with gross motor subscores. These findings on the Toddle TDI, a single score representing multiple gait parameters, are in contrast to findings on individual gait parameters; no one gait parameter was significantly different for all three groups of toddlers[16].

Sensitivity of Toddle TDIs ≤ 80 to gross motor scores ≤ 5 was 88%. Furthermore, the three toddlers who walked with handheld-assist received the same gross motor score, but received

Toddle TDIs of -48, 18, and 43, representing a spread of 9 SDs; this suggests the possibility that the Toddle TDI may be more sensitive to gradations of ability.

The Toddle TDI's lack of correlation to fine motor is an encouraging sign of discriminant validity and specificity to gross motor. Specificity of Toddle TDIs ≤ 80 to gross motor scores ≤ 5 was 83%, reflecting 7 true positives, 12 false positives, 59 true negatives, and 1 false negative. Follow-up of this cohort's diagnoses and gross motor function at age 7 is planned, and may clarify whether the 12 false positives reflect a greater sensitivity of the Toddler TDI than the BSID-III to gait function, or whether the false positives reflect current limitations of the Toddle TDI. An increased sample size may improve cutoff selection for screening purposes, further improving sensitivity and specificity. Lower Toddle TDI scores correlated with later independent walking; this is consistent with the current clinical use of delayed motor for detecting motor impairment. Taken together, these results suggest that the Toddle TDI is a sensitive, specific measure of gross motor function of gait in children aged 18-22 months, and is more revealing than individual gait parameters such as velocity.

In the first 2 months after onset of independent walking, toddler gait changes rapidly, and the Toddle TDI should be interpreted in this context.[16,23] However, by 18-22 months approximately 6-10 months of walking experience would be expected[10]; <2 months likely reflects gross motor delay, and a low Toddle TDI should not be dismissed on the basis of walking experience. After 2 months, walking experience is not a likely confound and the score may be interpreted as usual.[18]

Conducting the Toddle TDI is practical for clinical settings. Coaxing toddlers to complete 2-3 usable walks on a pressure-sensitive mat typically requires 5-10 minutes, and can be done by any pediatric clinician. Clinic visits between the ages of 18-22 months are standard-of-care, and thus the Toddle TDI can be administered impromptu during a standard visit, at the same appointment in which a clinician develops concerns about motor development. The Toddle TDI is proposed as a more widely-available screening tool which may enable gross motor assessment for more children than can receive a BSID-III; it is not intended to replace the BSID-III. Although not intended as a supplement to the BSID-III, it could be indicated for children who have received a BSID-III and for whom more specific information on gait function is desired.

A pressure-sensitive mat is a major investment; however, the mats are portable and can be shared between clinics, if follow-up schedules are coordinated. Although optimal, a pressure-sensitive mat is not required to calculate the Toddle TDI: any accurate measurement of the seven gait parameters will work equivalently for calculating the Toddle TDI. For example, a combination of high-speed video and footprints on paper is possible, though considerably more burdensome, for clinics without access to a mat. Gait-parameter detection algorithms for lightweight wearable inertial sensors are currently in development and may soon offer an inexpensive easy-to-use option for clinics. Entering the gait parameters into the included supplementary spreadsheet will output the Toddle TDI.

Limitations

The Toddle TDI quantifies deviation of gait from average; it reflects whether a child's walking is different from average, but cannot reveal the cause of the difference. A low Toddle TDI does not necessarily indicate an immature or impaired gait pattern; it could indicate an advanced gait pattern or theoretically a gait pattern that is simply uniquely 'expressive,' without reflecting

impairment. The Toddle TDI is intended to augment clinical expertise with a quantitative analysis. It should be used when there is parental or clinical concern about gross motor delay. Applying the Toddle TDI to apparently-TD toddlers could result in advanced walkers—whose gait patterns might be different from typical as a result of increased mastery—receiving a low Toddle TDI and being misidentified as delayed.

The Toddle TDI demonstrated important associations with prematurity and BSID-III outcomes. However, given the small sample size used in PCA analysis, it is possible that the specific component structure used to calculate the Toddle TDI would be different for a larger sample. Future studies should test the component structure with a larger number of TD participants. Follow-up of participants' gross motor function as they age will further clarify the clinical relevance of the Toddle TDI as a screening tool.

Conclusion

The Toddle TDI is an objective single-score index representing toddler gait deviation from typical. The Toddle TDI was significantly lower for preterm toddlers compared to TD toddlers, and significantly lower for preterm toddlers with <85 versus ≥ 85 BSID-III motor composite scores; additionally, preterm toddlers scoring ≥ 85 had significantly lower Toddle TDIs than TD toddlers. The Toddle TDI correlated with BSID-III gross motor and not fine motor subscores, and was more revealing than any single gait parameter. The Toddle TDI is quick and simple to administer in a clinic setting. Thus, the Toddle TDI may be a useful clinical tool for detecting gross motor delay in 18-22 month-old children.

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Table 1: Participant characteristics for all TD and preterm toddlers, and for the subset of preterm toddlers with ≥ 85 or < 85 BSID-III motor composite scores.

	TD	Preterm		
		All	≥ 85	< 85
Sex, female/male n =	18/24 42	48/33 81	41/26 67	5/7 12
Gestational age, weeks-days n =	39-5 (1-2) 39	28-6 (2-3) 81	28-6 (2-3) 67	27-5 (2-3) 12
Age at follow-up, months n =	19.9 (1.2) 42	20.2 (1.0) 81	20.2 (1.0) 67	20.0 (0.9) 12
Walking experience at follow-up, months n =	8.0 (2.0) 41	6.9 (3.3) 72	7.4 (2.9) 60	3.7 (3.9) 10
Age walked independently, months n =	12.0 (1.5) 41	13.1 (2.6) 69	12.6 (2.3) 59	15.4 (3.4) 8

Figure Captions

Figure 1: Box plots of temporal-spatial gait parameters for preterm children scoring < 85 on the BSID-III composite motor (white), preterm children scoring ≥ 85 (light gray), and TD children (dark gray). Midline represents the median, with box edges representing outer quartiles and whiskers representing range.

Figure 2: (A) Mean Toddler TDIs for preterm compared to TD children ($p = 0.003$), (B) and for preterm children with composite motor scores < 85 compared to those with ≥ 85 ($p = 0.004$) and TD children ($p < 0.001$), as well as preterm children scoring ≥ 85 compared to TD children ($p = 0.046$).

Figure 3: Toddler TDIs compared to BSID-III (A) gross motor, (B) fine motor, and (C) composite motor scores. Open circles represent children unable to walk independently, who walked with handheld assist.

Temporal-Spatial

Temporal

Spatial

A

B

A **B** **C**

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