



# Multiplanar kinematic deviations in idiopathic toe walking: A comparison with voluntary toe walking gait

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## ABSTRACT

**Introduction:** Idiopathic toe walking (ITW) refers to persistent toe walking beyond the age of three with no known neuromuscular causes. While ITW is primarily characterised by excessive ankle plantarflexion, multiplanar lower limb and segmental foot kinematic deviations remain underexplored. It is also unclear whether these deviations are merely biomechanical consequences of toe walking or specific to ITW.

**Research Question:** How does the gait pattern in children with ITW differ from typically developing children during normal walking (TD-N) and voluntary toe walking (TD-TW)?

**Methods:** This retrospective study included 44 children with ITW, and 44 typically developing children walking in a normal heel-toe pattern as well as voluntarily walking on toes. Three-dimensional lower-limb and multi-segment foot kinematics were collected, and joint kinematics was analysed using one-dimensional statistical parametric mapping adjusted for speed and age.

**Results:** Both toe-walking groups showed reduced step length and velocity, compared to TD-N, while only the TD-TW group walked with reduced step width relative to TD-N. ITW-specific deviations (compared to TD-TW) included excessive ankle plantarflexion at mid-swing, increased knee and hip flexion in swing and external hip rotation.

**Significance:** Voluntary toe walking does not fully replicate the gait pattern seen in ITW, suggesting the ITW gait pattern represents adaptations beyond biomechanical consequences of walking on toes.

## 1. Introduction

Toe walking, defined as a gait pattern characterised by the absence of heel strike at initial contact, is commonly observed in early childhood [1]. While most children outgrow this pattern, around 5% of children continue to walk on their toes [2]. In cases where toe walking persists after the age of three, the diagnosis of idiopathic toe walking (ITW) is typically made after ruling out other possible underlying conditions, such as cerebral palsy and muscular dystrophy [3]. Children with ITW have been shown to exhibit poor balance [4] and postural instability [5], increased fall risk [6], and impaired health-related quality of life (HRQOL) [7]. Despite its impact, it remains difficult to make well-informed treatment decisions without a clear understanding of the

underlying pathomechanics.

Previous studies have examined ITW by quantifying lower limb kinematics during gait, consistently reporting excessive ankle plantarflexion during both stance and swing phases, as well as reduced knee extension at initial contact [8–10]. Children with ITW also tend to walk with greater knee and hip flexion during swing to aid foot clearance [8]. Although numerous studies have characterised gait kinematics in ITW, most have focused primarily on sagittal plane deviations from level walking, thereby failing to capture the full extent of any multiplanar adaptations. The limited use of multi-segment foot models in prior studies may also have hindered accurate characterisation of foot and ankle kinematics in ITW [10]. Furthermore, children with ITW have been shown to walk at a slower speed, and it remains unclear which

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movement patterns are inherent to the pathology versus those attributable to the reduced walking speed [11].

One complication of studying idiopathic toe walkers is that walking on toes, even when voluntary, leads to altered kinematic patterns compared to level walking. This makes it challenging to determine which deviations are caused simply by walking on toes, and which are specific to ITW as a condition. It has been suggested that mimicking pathological gait in typically developing individuals can provide a better understanding of the pathology by separating primary deviations from secondary effects, such as those representing the biomechanical consequence of excessive ankle plantarflexion.

This study aims to characterise how multiplanar lower limb and foot kinematics in children with ITW differ from those of typically developing (TD) children during voluntary toe walking (TD-TW). It is hypothesised that, while sagittal plane differences will largely reflect the mechanics of walking in the absence of heel contact, additional differences in the frontal and transverse planes will be observed. It is also expected that unique deviations from level walking in ITW that are not replicated during TD-TW will be observed, which may represent adaptations linked to the underlying pathology.

## 2. Methods

### 2.1. Participants

This retrospective study included 44 children with ITW (mean age =  $12.2 \pm 2.7$ ) and 44 typically developing peers (mean age =  $10.8 \pm 3.2$  years). Data were extracted from the Oxford Gait Laboratory database under research ethics approval (21/LO/0426) and included demographics and gait assessments conducted between March 2021 and November 2023. Typically developing children were recruited to assist in developing a normative reference dataset. Children in the ITW group were referred to the Gait Lab for assessment of toe-walking, and the diagnosis of ITW was confirmed by clinicians.

### 2.2. Data collection

Joint kinematics were captured using a 16-camera T-series motion capture system (Vicon, Oxford, UK) operating at 100 Hz. Ground reaction forces were recorded using three floor-embedded force plates (OR-6, AMTI, Watertown, MA, USA) sampling at 1000 Hz, in order to determine gait events.

Marker placement was based on a modified conventional gait model [12] and the Oxford Foot Model [13]. Pelvic angles were calculated using the rotation sequence of transverse, frontal, then sagittal, as described by Baker et al. [14]. Hip joint centres were estimated using the regression method of Harrington et al. [15].

Participants were asked to walk barefoot along a 10-meter walkway at a self-selected speed. Typically developing participants completed both normal walking and voluntary toe-walking trials, while participants with ITW walked using their habitual toe-walking gait. For the voluntary toe-walking condition, participants were instructed to walk “as high as possible” on their tiptoes. Data was collected after a period of familiarisation. Each participant completed a minimum of six walking trials to ensure sufficiently representative data was collected.

### 2.3. Data processing

Marker trajectories were processed in Vicon Nexus (version 2.12). Knee angles in the transverse and frontal planes were not analysed, as they are not reliably represented using the PlugInGait conventional gait model [16]. Gait cycles were defined based on foot strike events, which were identified using a 10 N vertical force threshold on the ground reaction force in line with routine practice at the Gait Laboratory. All event timings were verified visually. Kinematic waveforms were time normalised to 0–100% of the gait cycle. For each participant, one

representative gait cycle was selected based on the minimum root mean square difference between the individual trials and the mean of all trials for that participant. A representative stride was used rather than mean traces to avoid oversmoothing of features inherent in averaged trajectories due to temporal misalignment [17].

Spatiotemporal parameters were calculated, including step length, step width, and walking velocity, using the ezc3d library in Python [18], and were normalised by leg length following the dimensionless approach described by Hof et al. [19].

### 2.4. Statistical analysis

Two primary comparisons were performed:

(1) ITW vs TD-TW to identify idiopathic toe-walking-specific features, and (2) TD-N vs both toe-walking patterns (TD-TW and ITW) to quantify overall deviation from typical gait.

For spatiotemporal parameters, pairwise comparisons between TD-N and TD-TW (within-subject) were conducted using paired two-tailed *t*-tests, while comparisons between TD and ITW groups were evaluated using unpaired two-tailed *t*-tests.

Comparisons of lower limb joint kinematics and foot angles were conducted using one-dimensional Statistical Parametric Mapping (SPM) in Python. Both within-subject (paired) comparisons (TD-N vs TD-TW) and between-subject (unpaired) comparisons (ITW vs TD-TW; ITW vs TD-N) were implemented within the SPM General Linear Model (GLM) framework. Adjusted GLM-SPM analyses included age and normalised gait speed as covariates to account for age- and speed-related effects. Covariate effects and unadjusted SPM analyses (standard paired or unpaired SPM(*t*) tests) are provided in the Appendix for completeness. Only results with statistically significant outcomes ( $p < 0.05$ ) are reported.

## 3. Results

### 3.1. Spatiotemporal parameters

Comparison of spatiotemporal parameters (Fig. 1) revealed distinct gait characteristics across groups. Normalised walking velocity was lowest in ITW, followed by TD-TW, then TD-N. Both toe-walking groups (ITW and TD-TW) demonstrated significantly shorter normalised step lengths compared to TD-N. Normalised step width was significantly reduced in the TD-TW group relative to ITW.

### 3.2. Lower limb kinematics

The group-averaged kinematic waveforms for the lower limb and multi-segment foot across the gait cycle are presented in Figs. 2 and 3, respectively. The key residual group differences are summarised in Table 1.

#### 3.2.1. Pelvis

In the sagittal plane, both ITW and TD-TW demonstrated greater anterior pelvic tilt compared to TD-N, while no significant difference was observed when comparing ITW and TD-TW. In transverse and frontal planes, significant deviations were detected only between TD-TW and TD-N around initial contact and foot off.

#### 3.2.2. Hip

In the sagittal plane, ITW had significantly greater hip flexion than TD-TW throughout the entire swing phase. Compared to TD-N, ITW showed a smaller-magnitude deviation limited to only part of swing. In the transverse plane, all three groups demonstrated significant differences during midstance. Both TD-TW and ITW exhibited increased external rotation, with the level of deviation being more significant in ITW. In the frontal plane, no significant differences were found between ITW and other groups.

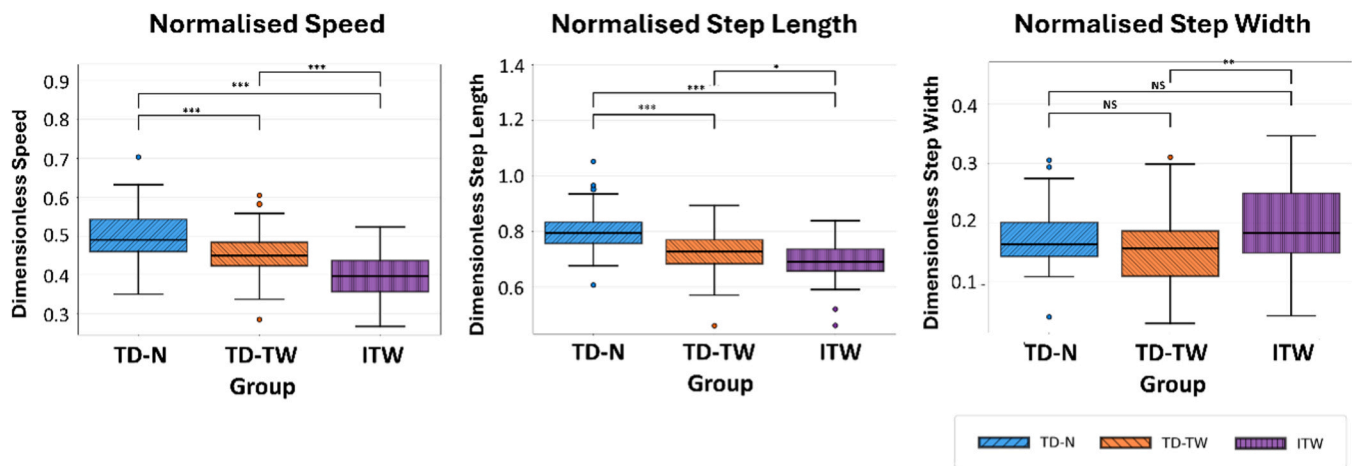


Fig. 1. Comparisons of spatiotemporal gait parameters. Boxplots show normalised speed, step length and step width for TD-N, TD-TW, and ITW. Significance differences in pairwise comparisons are indicated by asterisks (\* $p < 0.05$ ; \*\* $p < 0.01$ ; \*\*\* $p < 0.001$ ).

### 3.2.3. Knee

Significant differences were observed in early swing for the knee joint in the sagittal plane. Both toe-walking groups showed reduced peak knee flexion in swing (even after accounting for walking speed). This was more pronounced in the TD-TW group compared to the ITW group.

## 3.3. Multi-segment foot kinematics

### 3.3.1. Hindfoot relative to Tibia

Hindfoot–tibia kinematics showed that increased plantarflexion relative to TD-N—a defining feature of toe walking—was observed in both ITW and TD-TW. However, ITW differed from TD-TW only briefly during mid-swing, where ITW demonstrated additional plantarflexion that voluntary toe walking failed to replicate. In contrast, the transverse and frontal planes showed no significant differences involving ITW, with deviations appearing only between TD-TW and TD-N.

### 3.3.2. Forefoot relative to hindfoot

In the sagittal plane, TD-TW exhibited greater plantarflexion than both ITW and TD-N around foot strike, whereas ITW showed no significant deviation from TD-N. In the transverse and frontal planes, ITW again showed no significant differences relative to TD-N, while TD-TW demonstrated reduced abduction throughout the gait cycle in the transverse plane and small increases in pronation around foot strike and pre-swing in the frontal plane.

## 4. Discussion

The hypothesis that children with ITW exhibit deviations from level walking that are different from those in TD-TW was supported by our findings. As expected, sagittal-plane deviations, particularly excessive ankle plantarflexion, were observed in both ITW and TD-TW, alongside additional ITW-specific deviations. This study is the first to combine a multi-segment foot model with voluntary toe-walking comparators to characterise ITW across all three planes, enabling differentiation between adaptations specific to ITW and those attributable to the generic biomechanical consequences of forefoot loading.

### 4.1. Spatiotemporal parameters

Analysis of spatiotemporal parameters revealed clear group differences in normalised walking speed: children with ITW walked significantly slower than both TD-TW and TD-N, and TD-TW was also slower than TD-N. This finding is contradictory to previous literature which reports no significant reduction in walking speed in ITW, likely

reflecting the heterogeneous presentation of the condition [20,21]. Step length followed a similar pattern, with ITW demonstrating the shortest step length, followed by TD-TW. Interestingly, although slower gait is typically associated with increased step width—a strategy thought to enhance mediolateral stability—children with ITW did not exhibit wider steps than TD-N. Indeed, TD-TW showed a significantly narrower step width [22,23]. Taken together, these results suggest that the altered spatiotemporal characteristics of ITW may arise from factors beyond direct consequences of toe walking.

### 4.2. Multiplanar lower limb kinematics

This study revealed multiplanar deviations in ITW, supporting the view that ITW is not defined solely by sagittal-plane plantarflexion but involves broader adaptations throughout the lower limb. Both ITW and TD-TW displayed excessive plantarflexion, consistent with previous work showing that toe walking disrupts all three ankle rockers [8,9]. At the knee and hip, our findings align with a previous study that simulated equinus through dorsiflexion restriction, demonstrating reduced knee extension at initial contact and mid-stance, and reduced hip extension in terminal stance [24]. A key distinction emerged when comparing ITW and TD-TW: TD-TW displayed greater reduction in peak knee flexion in swing than ITW, likely because TD-TW participants regained near-normal dorsiflexion during swing, reducing their reliance on knee flexion for toe clearance, while the greater reliance on knee flexion in ITW may represent compensation for reduced ankle dorsiflexion, as ankle contracture is commonly seen within this population. Although some studies have reported increased posterior pelvic tilt in toe walking [8]; our ITW cohort demonstrated greater anterior pelvic tilt. These contrasting patterns highlight the variability in adaptive strategies adopted by children with ITW and reinforce the need for personalised intervention plans.

### 4.3. Segmental foot kinematics

Children with ITW demonstrated foot kinematic patterns surprisingly similar to TD-N, replicating forefoot–hindfoot and hindfoot–tibia motion across both transverse and frontal planes. The only consistent deviation was reduced hindfoot–tibia dorsiflexion. This may be due to the inability of participants to fully replicate the level of heel elevation during voluntary trials—a limitation previously described when attempting to mimic equinus gait in able-bodied participants [25].

In contrast, TD-TW demonstrated markedly different foot kinematics from TD-N, consistent with previous work on voluntary toe walking [26, 27], including increased forefoot plantarflexion, increased hindfoot

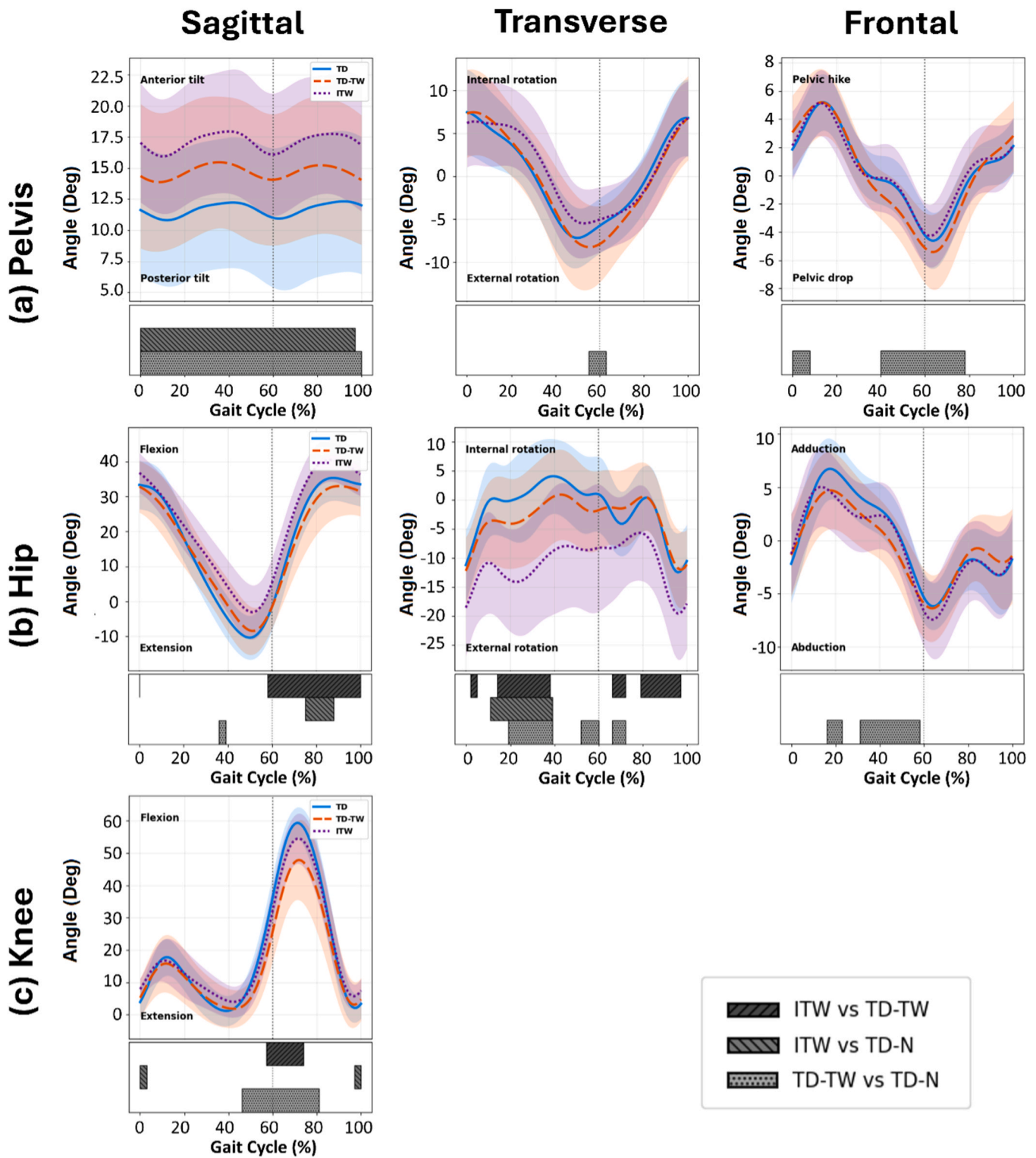


Fig. 2. Comparison of pelvis, hip, and knee kinematics across the gait cycle for ITW, TD-TW and TD-N. Mean curves are shown for each group in the sagittal (left column), transverse (middle column), and frontal (right column) planes, with bars underneath showing statistically significant regions identified using Statistical Parametric Mapping (SPM), adjusted for age and walking speed.

adduction, and altered forefoot-hindfoot joint motion.

#### 4.4. Clinical implications

Current approaches to ITW management often focus on correcting sagittal-plane deficits such as absent ankle rockers, with tendon

lengthening used to restore dorsiflexion [28,29]. However, this strategy may overlook persistent transverse-plane abnormalities—such as external hip rotation—which are known to remain after intervention [30]. Incorporating objective, multi-planar gait analysis may therefore improve diagnostic precision and guide more targeted intervention planning.

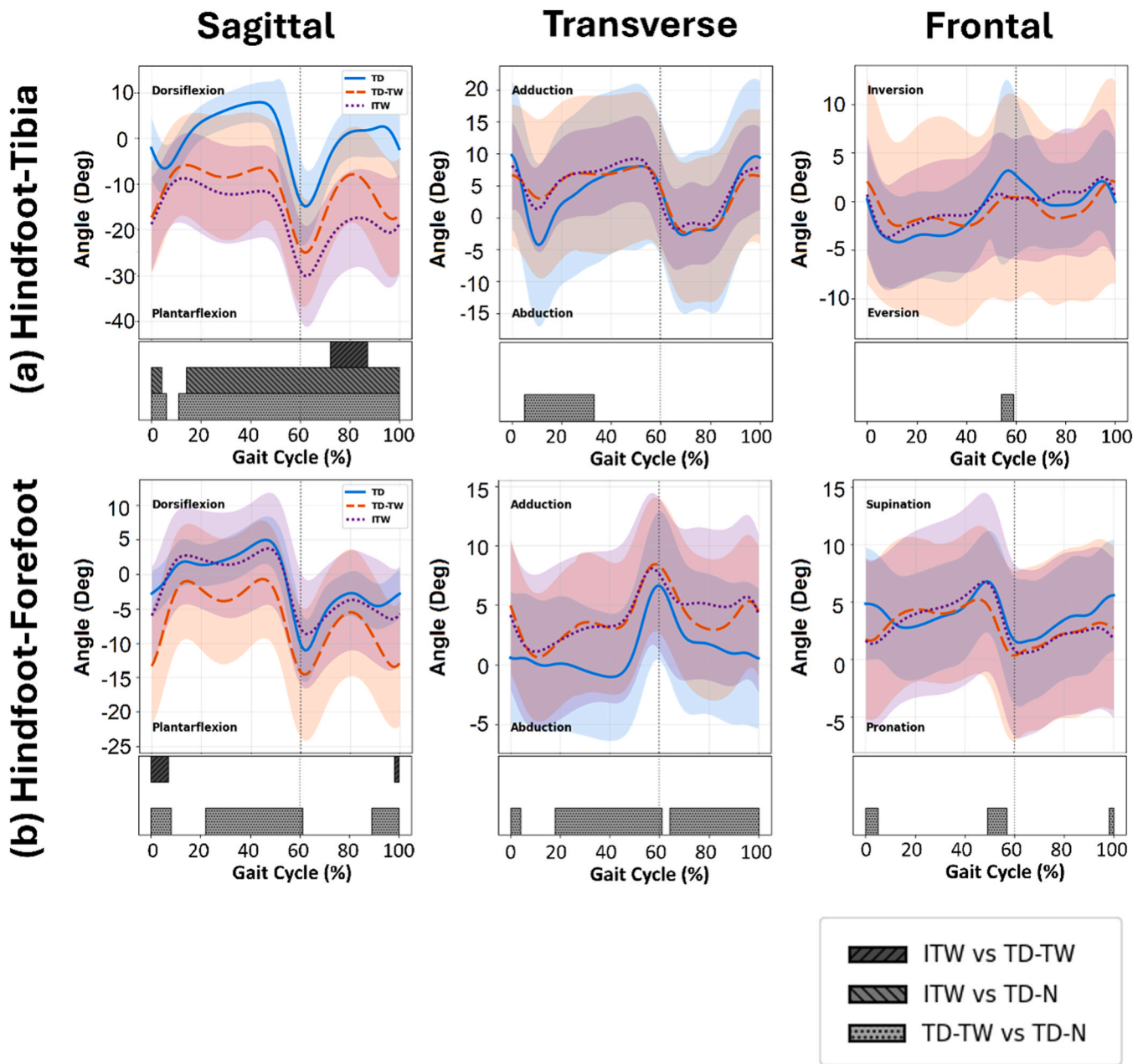


Fig. 3. Comparison of foot kinematics across the gait cycle for ITW, TD-TW and TD-N. Mean curves are shown for each group in the sagittal, transverse, and frontal planes, with bars displaying statistically significant regions after adjustment for age and walking speed.

Table 1  
Summary of ITW-specific deviations not seen in TD-TW relative to TD-N.

Joint	Deviation unique to ITW (not seen in TD-TW relative to TD-N)
Pelvis	No unique deviation observed.
Hip	(1) greater hip flexion during swing; (2) excessive external rotation throughout the gait cycle
Knee	Reduced knee flexion in swing, but not to the extent of TD-TW.
Hindfoot-Tibia	Greater plantarflexion at mid-swing.
Forefoot-Hindfoot	Similar to that of normal TD-N, rather than TD-TW.

4.5. Study limitations

A key limitation relates to the use of voluntary toe walking in typically developing children as a comparator. While commonly used and

useful for distinguishing primary from secondary deviations, the validity of mimicking pathological gait remains uncertain. Children with ITW develop long-standing adaptations in muscle-tendon behaviour and segmental coordination through habitual use [32], whereas TD participants are performing an unfamiliar task. Some differences between ITW and TD-TW may therefore reflect unfamiliarity rather than pathology-specific adaptations.

Another limitation of this study is the absence of radiographically derived offsets to define foot segment coordinate systems. Although the Oxford Foot Model (OFM) is widely used and clinically meaningful, it relies on external markers to infer bone orientation. Prior work has shown that transverse -plane is particularly sensitive to marker placement variability [27]. This may explain the lack of significant differences in this plane. Imaging-based approaches could improve anatomical accuracy, particularly in populations with foot deformity [31], though such methods are rarely feasible in routine clinical

practice. Consequently, conclusions regarding the limited transverse- and frontal-plane differences should be interpreted cautiously.

## 5. Conclusion

This study provides the first multiplanar characterisation of lower-limb and foot kinematics in children with ITW using a multi-segment foot model. By comparing ITW with both TD-N and TD-TW, we demonstrated that ITW presents additional deviations from level walking not reproduced during voluntary toe walking—including greater hip flexion in swing, external hip rotation, and altered knee kinematics. Although voluntary toe walking reflects an unfamiliar gait pattern, rather than long-term neuromuscular adaptation, it captures the mechanical consequences of forefoot loading and thus offers a useful reference for understanding which deviations are inherent to toe walking versus those that are pathology specific.

## CRedit authorship contribution statement

**Alpesh Kothari:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Amy Zavatsky:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Julie Stebbins:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Halenur Evrendilek:** Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Ching Hang Chiu:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization.

## 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.

## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.gaitpost.2026.110134](https://doi.org/10.1016/j.gaitpost.2026.110134).

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