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# Comparing Theia3D software versions for gait kinematics in typically developing children

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ABSTRACT

Markerless motion capture systems such as Theia3D offer an alternative to traditional marker-based approaches for measuring gait kinematics. As the underlying algorithms continue to evolve, successive software updates may introduce differences in kinematic outputs. However, the extent of these differences is not well known. The purpose of this study was to quantify inter-version differences in Theia3D-derived gait kinematics in typically developing children. Sixteen typically developing children completed five barefoot walking trials at a self-selected speed. Video data were processed using three versions of Theia3D (v2022.1.0.2309, v2023.1.03161 and v2024.1.24). Inter-version differences were assessed across joints and planes of motion using one-dimensional Statistical Parametric Mapping (1D-SPM) repeated measures ANOVA, with planned pairwise comparisons between sequential releases. Significant differences were identified across all joints and planes of motion. The largest differences were observed between v2022 and v2023, with smaller and more localised differences between v2023 and v2024. Mean differences were generally below 6°, with larger deviations observed in the transverse plane at the ankle and foot and in the sagittal plane at the trunk, pelvis and hip. Differences were not consistent across versions, with some angles demonstrating patterns that reverted towards earlier outputs. These findings demonstrate that software version does influence motion capture kinematics. While differences are small at some joint levels, there is potential for software version to influence interpretation in certain contexts, particularly in longitudinal assessments. Obligatory reporting of software version and data reprocessing are recommended when using markerless systems.

## 1. Introduction

Marker-based motion capture remains the clinical standard for three-dimensional gait analysis. However, it requires precise marker placement on anatomical landmarks, specialist expertise, and substantial preparation time, and remains susceptible to soft tissue artefact and operator-dependent variability (Wade et al., 2022). Markerless motion capture systems have emerged as an alternative, using machine learning-based pose estimation algorithms to reconstruct three-dimensional joint kinematics from synchronised video data but also remain susceptible to soft tissue artefact and occlusion challenges. Theia3D (Theia Markerless Inc., Canada) is a commercially available markerless system that has demonstrated acceptable agreement with marker-based models for lower limb gait kinematics in adults and children (Kanko, E. K. Laende, *et al.*, 2021; Wren, Isakov and Rethlefsen, 2023; D'Souza, Siebert and Fohanno, 2024; Wishaupt et al., 2024; Greaves et al., 2025; Kearney et al., 2025). Reliability studies have also reported low inter-session measurement error during walking (Kanko, E. Laende, *et al.*, 2021; Riazati et al., 2022; Outerleys et al., 2024; Augustine et al., 2025), supporting its use in both research and emerging clinical contexts.

Markerless motion capture measurement quality is influenced by multiple factors, including clothing (Augustine et al., 2025), lighting and camera positioning (Thomas et al., 2026), and camera number and configuration (Walker et al., 2026), as well as the subsequent software processing applied to the captured video. Markerless motion capture systems undergo regular software development as pose estimation algorithms, training datasets and biomechanical models are refined. Such updates may be introduced to improve tracking accuracy and robustness across participants and movement tasks, increase computational

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efficiency, or improve model generalisability. While these developments may enhance system performance, they also create an important methodological consideration because identical video may produce different kinematic outputs when processed using different software versions. This is particularly relevant for longitudinal studies, normative databases, or multicentre collaborations where consistency between software versions is required. To mitigate these challenges, software providers could prioritise refinement towards more stable models requiring less frequent modification or provide distinct model packages optimised for specific movement or applications. A recent review of markerless motion capture literature highlighted inconsistent reporting of software versions across studies, despite ongoing algorithmic development, further complicating interpretation and comparison of findings across laboratories and time points (Varcin and Boocock, 2026). The review evidences that previous studies have evaluated agreement between Theia3D and established marker-based approaches across a range of populations and software versions. However, criterion validity and software-version consistency represent distinct measurement questions. Comparison with a reference system does not determine whether identical video data will produce comparable kinematic outputs when processed using successive software releases.

The impact of inter-version differences may be particularly relevant in paediatric gait analysis, where children commonly undergo repeated assessments to monitor development, evaluate intervention outcomes, or track disease progression. In this context, distinguishing true biomechanical change from software-induced differences is critical for accurate clinical interpretation. However, the extent to which successive Theia3D releases influence gait kinematics in paediatric populations remains unclear. Therefore, the purpose of this study was to compare lower limb gait kinematics derived from three versions of Theia3D (v20221.0.2309, v2023.1.03161, and v2024.1.24) in typically developing children. Inter-version differences were quantified across joint levels and planes of motion to determine the potential impact of software updates on gait analysis.

## 2. Methods:

### 2.1. Participants

Sixteen typically developing children (10 female, 6 male, age 9.7 ± 3.0 years, height 1.46 ± 0.17m, mass 38.03 ± 11.64kg) completed five barefoot overground walking trials at a self-selected speed in the North West Movement Analysis Centre (NWMAC) at Alder Hey Children's Hospital gait laboratory. Participants were free from any musculoskeletal injury or conditions that would affect their walking. This cohort represents a subset of participants included in a previous publication with inclusion based on the ability to reprocess data with earlier software versions (Kearney et al., 2025) available in Supplementary Fig. 1. Ethical approval was granted as part of a local clinical audit (Audit number: 6921), and written informed consent was obtained from each participant's legal guardian.

### 2.2. Experimental set up and data collection

Ten Qualisys Miqus video cameras (1920×1080 resolution, RGB) recorded synchronised data at 100 Hz. Eight cameras were positioned around the gait laboratory off a wall-mounted rig at 2.15m height and oriented towards the centre of the capture area. Two cameras were positioned at a fixed height of 0.92m to provide dedicated sagittal and frontal plane views. The camera arrangement was configured to maintain participant visibility during overground walking in both directions through the laboratory. The walkway, incorporating the integrated force platforms, was positioned 5.62m from the front, rear and right walls of the laboratory and 4.40m from the left wall. The calibrated capture volume encompassed the majority of this laboratory area, including the walkway and integrated force plates. Further details of the experimental set up are provided in Kearney et al. (2025). Four AMTI Optima-MMS force plates (MMS400600) sampling at 100Hz were used to collect ground reaction forces. Data collection was conducted under consistent, well-lit laboratory conditions and lighting was maintained throughout all capture sessions. Given the controlled lighting conditions, automatic exposure was disabled and all cameras were set to an exposure time of 9940μs. All were calibrated simultaneously with a shared global coordinate system using Qualisys Track Manager. Participants wore minimal tight-fitting clothing and all 2D video contained participants walking with markers attached. Five valid walking trials were collected and recorded for analysis for each participant at a self-selected walking speed to provide a representative estimate of gait while reducing the influence of stride-to-stride variability. Each trial comprised one pass along the laboratory walkway. One completed left-sided gait cycle was selected from each trial, resulting in five gait cycles per participant for analysis. These video data were collected synchronously alongside marker-based motion capture as part of a larger study comparing Theia3D with the Conventional Gait Model (CGM1.1), published previously by Kearney et al. (2025). Marker-based data from the same 16 typically developing children included in the present study are shown in the Supplementary Material for contextual comparison only and were not included in the primary statistical analysis. Gait events were defined manually by experienced clinicians, using synchronised video and ground reaction force visualisation in Qualisys Track Manager, following the clinical gait laboratory procedure described in Kearney et al. (2025). Clinicians undertaking this processing had previously passed a repeatability assessment for gait-event detection. Events were defined once and the same events were applied across all three software versions to ensure identical temporal normalisation.

### 2.3. Markerless processing across software versions

The same archived raw video files were processed independently using three versions of Theia3D (Theia Markerless Inc., Kingston, Ontario, Canada): (1) Version 20221.0.2309 (v2022), (2) Version 2023.1.03161 (v2023) and (3) Version 2024.1.24 (v2024). Theia3D reconstructed 3D segment pose using a full-body inverse kinematics model with a modified Euler sequence for the pelvis (pelvis: six degrees of freedom; hip and ankle: three degrees of freedom; knee: two degrees of freedom). Processed data were exported as .c3d files containing 4×4 segment pose matrices, representing the position and orientation of each segment coordinate system across time. To isolate software version effects from user adjustable filtering choices, filtering within Theia3D was disabled for all three versions. Each unfiltered version specific .c3d file was imported into Visual3D (v2024.7.2, HAS Motion, Kingston, Ontario, Canada), where skeletal models were generated directly from the segment pose matrices and the same pipeline was used across each dataset to calculate and extract kinematics. A fourth-order zero-lag Butterworth low-pass filter (6Hz) was applied uniformly to all datasets in Visual3D.

### 2.4. Statistical analysis

Following time normalisation to 100% of the gait cycle, five left-sided gait cycles for each participant were ensemble-averaged to generate one participant-level mean waveform for each kinematic variable and software version. These participant-level mean waveforms were entered into the statistical analysis. To determine differences between Theia3D versions across the gait cycle, a one-dimensional Statistical Parametric Mapping (1D-SPM) repeated measures analysis of variance (ANOVA) was performed using the *spm1d* package (Pataky, 2010) in MATLAB (R2023a, The MathWorks Inc.). Software version was treated as the within-subject factor. Statistical significance was defined as the SPM {F} curve exceeding the critical threshold at $\alpha = 0.05$. Where a significant main effect of software version was identified, planned pairwise comparisons were restricted to sequential software

releases (v2022 vs v2023; v2023 vs v2024) using paired 1D-SPM t-tests. Alpha was adjusted for multiple comparisons using a Bonferroni correction across two sequential pairwise tests within each variable, yielding an adjusted alpha of 0.025. Mean differences between v2022 and v2024 were calculated to illustrate the cumulative effect of iterative updates and are presented in the difference curves within Fig. 2 but were not included in the statistical analysis because this would represent the effect of two sequential updates rather than the effect of an individual software update.

## 3. Results

A significant main effect of software version was identified across most joint levels and planes of motion. Supra-threshold clusters of difference were observed at the trunk, pelvis, hip, knee and ankle, with only minimal differences detected in trunk rotation. Post hoc comparisons revealed inter-version differences (Fig. 1) with differences between v2022 and v2023 observed at the trunk (tilt and obliquity), hip (adduction and rotation), knee (varus/valgus), foot progression angle, and ankle across all three planes of motion. Differences between v2023 and v2024 were observed at the pelvis (tilt and rotation), hip (flexion/extension and rotation), knee (varus/valgus), foot progression angle, and ankle (dorsiflexion and inversion).

The magnitude of inter-version differences were below 5° at most joint levels (Fig. 2). The largest mean differences between v2022 and v2023 were observed at the ankle in the transverse plane (-6.3°) and at the trunk in the sagittal plane (-5.1°), with mean differences typically ranging between -3.5° and 4.4°. Differences between v2023 and v2024 were of greater magnitude, ranging between -5.8° (foot progression and 4.8° pelvic tilt). Differences were distributed across both stance and swing phases depending on joint and plane of motion. Bidirectional changes were evident between v2022 and v2024 in the hip rotation, foot progression, ankle dorsiflexion and inversion graphs. At these joints, the mean difference curves were closer to zero, with smaller cumulative differences than consecutive differences.

Numerical results of the 1D-SPM repeated measures ANOVA are presented in Fig. 3. A significant main effect of Theia3D software versions ($P<0.05$) was identified for all kinematic variables, although the extent of significant differences varied between joints and planes of motion. Significant main effects were present throughout the entire gait

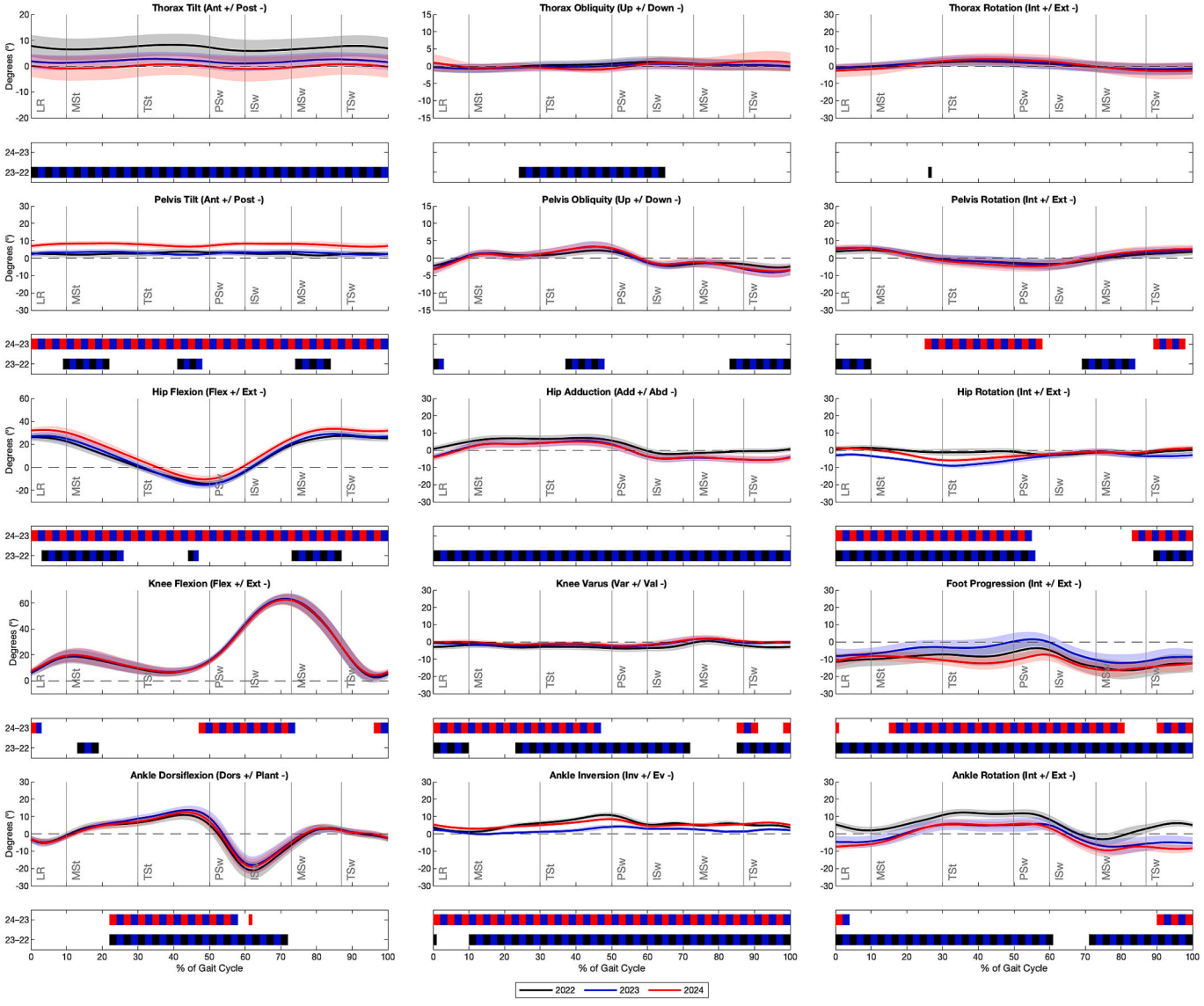



**Fig. 1.** Mean and 1SD kinematic waveforms for trunk, pelvis, hip, knee, and ankle across the gait cycle for Theia3D versions 2022, 2023 and 2024. Horizontal bars indicate phases of the gait cycle where significant differences were identified between consecutive versions (2022 vs 2023 – black and blue; 2023 vs 2024 – blue and red) using paired 1D-SPM t-tests. Horizontal bars are corresponding colours to the colour used in the kinematic curves.

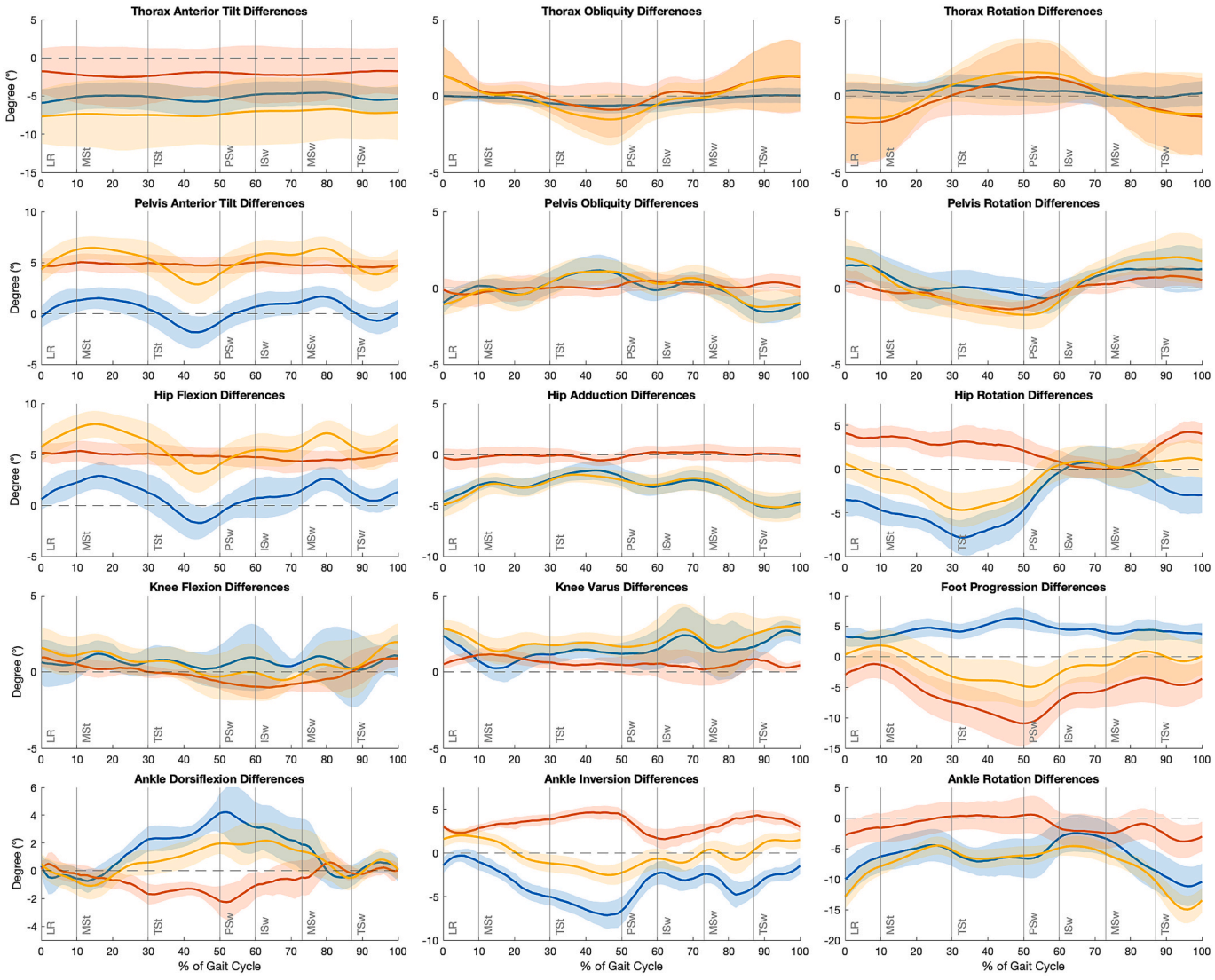



**Fig. 2.** Mean inter-version difference curves across the gait cycle for trunk, pelvis, hip, knee, and ankle kinematics. Differences are shown for consecutive comparisons (2022 vs 2023; 2023 vs 2024) and the cumulative comparison (2022 vs 2024). Positive and negative values indicate the direction of offset between versions. Blue line represents the difference curve between v2023 and v2022. Red line represents the difference curve between v2024 and v2023. Yellow line represents the difference between v2024 and v2022.

cycle for sagittal plane thorax, pelvis and hip kinematics, frontal plane hip, knee and ankle kinematics and transverse plane foot progression and ankle kinematics. For the remaining kinematic variables, significant main effects occurred across multiple discrete regions of the gait cycle.

## 4. Discussion

The present study identified statistically significant inter-version differences across most joint levels and planes of motion, with the largest number of differences observed between v2022 and v2023. This is consistent with the documented updates in the 2023 release notes, which included expansion of the training dataset, additional salient features and algorithmic refinements intended to improve tracking accuracy, alongside reported changes in hip joint centre estimation, global pelvis pose and ankle/foot kinematics relative to the 2022 version. Despite the widespread statistically significant differences, most inter-version mean offsets did not exceed ~5°. These values are comparable to previously reported differences between marker-based and markerless models and to measurement variability reported in repeatability studies of markerless gait analysis (Kanko, E. K. Laende, *et al.*, 2021; D'Souza, Siebert and Fohanno, 2024; Wishaupt et al., 2024; Greaves et al., 2025; Kearney et al., 2025). As such, the observed differences should be interpreted within the context of expected methodological variability rather than as large biomechanical deviations.

Changes in pelvic kinematics provide insight into the evolving model behaviour. Previous studies have reported a tendency for Theia3D to estimate sagittal plane pelvic kinematics closer to neutral compared to marker-based models (Kanko, E. K. Laende, *et al.*, 2021; Song et al., 2023; D'Souza, Siebert and Fohanno, 2024; Wishaupt et al., 2024; Kearney et al., 2025). In the present study, pelvic tilt remained similar (<5°) between v2022 and v2023 (Fig. 2) whereas v2024 demonstrated a consistent shift towards increased anterior tilt, aligning more closely with marker-based reference data (available in Supplementary Materia). This suggests that updates in v2024 may partially address previously reported offsets in pelvic orientation, although closer agreement with a marker-based model for pelvic tilt should not be interpreted as evidence that v2024 is universally more accurate. This interpretation is also consistent with documented changes introduced in the Apollo v2024 release, which revised aspects of the biomechanical model and segment pose outputs relative to earlier versions. These changes provide a possible explanation for the coordinated shifts observed in pelvic tilt and hip flexion between v2023 and v2024, although the proprietary nature

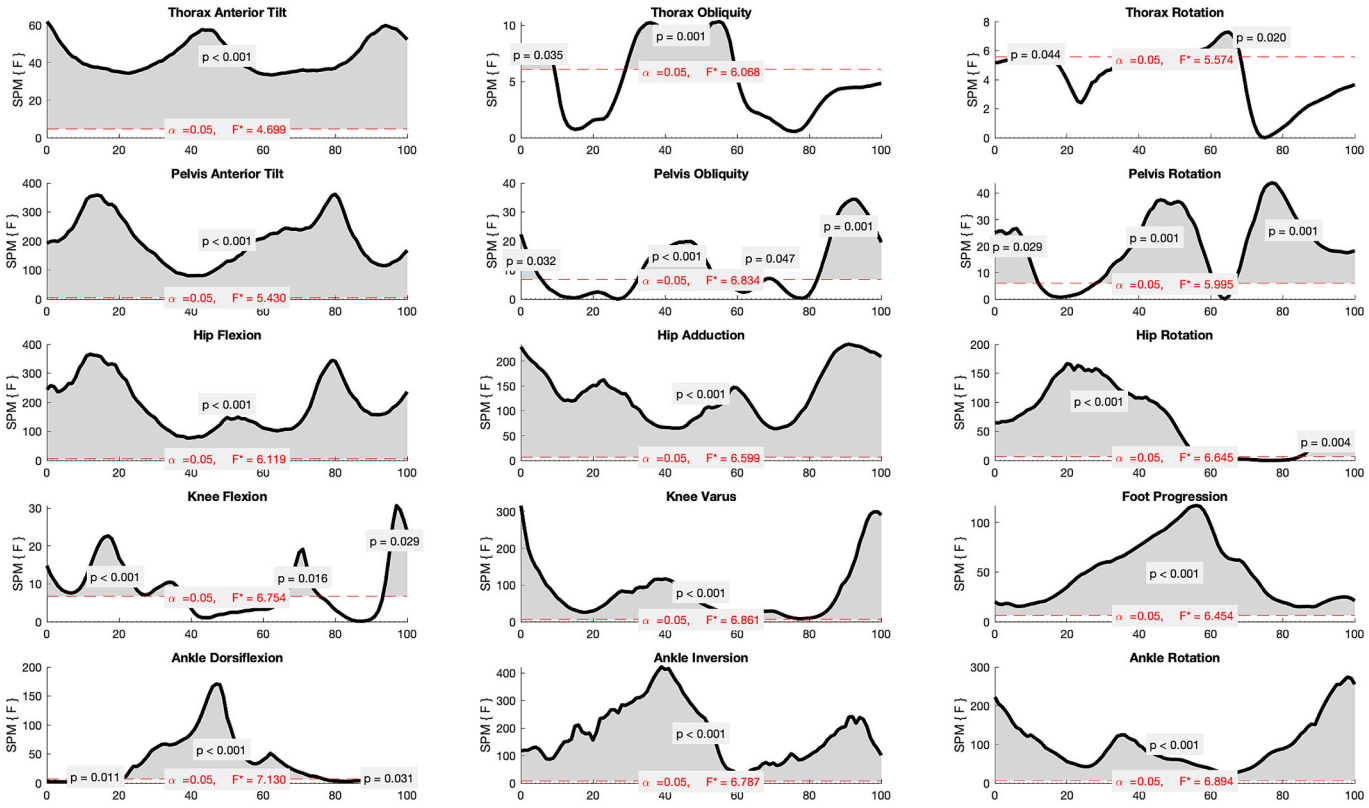



**Fig. 3.** SPM{F} curves from the 1D-SPM repeated-measures ANOVA testing the main effect of Theia3D software version across v2022, v2023 and v2024 for each joint and plane of motion. Grey shaded regions indicate suprathreshold clusters where the critical threshold exceeded ($\alpha = 0.05$), representing a significant main effect of software version. Reported p-values correspond to the cluster-level significance of each suprathreshold region. Where multiple p-values are shown within a subplot, these represent separate significant clusters occurring at different phases of the gait cycle and do not represent pairwise comparisons between the software versions.

of the underlying pose-estimation algorithm prevents direct attribution of each kinematic difference to a single software modification. Consistent with the principles of kinematic chain linkage where segments are coordinated and movement at one influences the others (Armand, Decoulon and Bonnefoy-Mazure, 2016; Alizadeh and Mattes, 2019; Favetta et al., 2022), this shift in pelvis orientation was accompanied by corresponding changes at the hip, with v2024 demonstrating increased hip flexion relative to v2023. In contrast, knee joint differences were smaller and phase-specific while ankle differences were limited to midstance through to early swing.

(Kwak et al., 2026)Differences at the ankle may partly reflect documented changes in distal segment estimation between software releases. In the 2023 release, Theia reported improved agreement in ankle inversion/eversion that accompanied changes in how the foot segment was oriented about its longitudinal axis, while some offset remained in the global foot angle used to represent toe-in/toe-out. These documented updates provide a plausible explanation for the inter-version differences observed in ankle inversion and foot progression angle in the present study. Distal segment tracking may also remain particularly sensitive to camera perspective, image quality and occlusion because of the smaller visual representation of the foot, with performance shown to vary across joints and planes of motion (Kwak et al., 2026). More generally, these findings suggest that software updates reflect refinements across multiple components of the processing pipeline, including pose estimation, segment definitions and joint-centre estimation, rather than changes occurring along a single consistent trajectory. However, the proprietary nature of the underlying pose-estimation algorithm means that the contribution of individual algorithmic changes to each joint- and plane-specific difference cannot be determined fully from the available documentation. Future work could extend our analysis by comparing version-specific 4x4 segment pose outputs or global segment orientations directly, which may help distinguish changes arising from segment pose estimation from those introduced through downstream joint-angle calculations.

Differences in the transverse plane were the most pronounced at the hip, with v2023 demonstrating external rotation during stance. This pattern deviates from expected gait behaviour in typically developing children where this may often be accompanied by corresponding foot rotation as one action observed during loading response (Perry, 2010) highlighting the clear distinction between Theia3D and traditional marker-based methods observed across the literature (Kanko, E. K. Laende, *et al.*, 2021; D'Souza, Siebert and Fohanno, 2024; Greaves et al., 2025; Kearney et al., 2025). The absence of a coordinated foot progression pattern suggests that these differences are more likely to be primarily attributable to modelling or pose estimation limitations rather than true biomechanical variation, as a genuine biomechanical effect would be expected to produce corresponding rotations across adjacent segments. Although v2024 appears to partially correct this, accurate estimation of axial hip rotation remains challenging even in marker-based systems (Camomilla, Dumas and Cappozzo, 2017; D'Isidoro, Brockmann and Ferguson, 2020). These findings therefore reflect ongoing challenges in resolving transverse plane kinematics and highlight the sensitivity of rotational measures to modelling assumptions.

The longitudinal clinical implications of these model changes remain unclear, particularly in the absence of evidence linking version-related differences to patient outcomes. However, the findings highlight the importance of maintaining consistency in software version when interpreting repeated assessments, allowing flexibility within the software to switch between versions and accessibility to reprocess when required. In paediatric gait analysis, where evaluations may be separated by

extended periods, changes in kinematics may reflect either true biomechanical adaptation or differences introduced through software updates. The most robust solution is to reprocess data using a consistent software, ideally the latest version, although this introduces practical considerations related to data storage, processing time, and workflow. The magnitude of differences observed in typical gait may be sufficient to influence interpretation in certain contexts, particularly where changes of a similar scale are used to inform clinical decisions; however, kinematic data are rarely considered in isolation and should be interpreted alongside broader clinical assessment.

These findings emphasise the importance of transparent reporting of software version in both research and clinical applications of markerless motion capture. As algorithms continue to develop, consistency in data processing becomes critical for comparison across studies and laboratories. Differences in modelling approaches, camera configurations, and data collection conditions may further influence kinematic outputs, reinforcing the need for clear methodological reporting (Kwak et al., 2026; Walker et al., 2026). Despite these considerations, the primary advantage of markerless systems remains their feasibility, enabling data collection in environments that are not accessible using traditional marker-based approaches (McGuirk et al., 2022). Ensuring consistency in processing and reporting will be essential to support the continued adoption and appropriate interpretation of markerless motion capture data.

This study has several limitations. Only three versions of Theia3D were used in this study, which may not represent the full range of versions currently used across research and clinical settings. Older versions may still be in use and further updates are likely as the software continues to develop. Not every update may contain model changes as some may address user interface or visual aspects of the software. We do not have a true gold standard reference for comparison to determine the accuracy of each version. Current clinical reference marker-based models are used widely despite recognised limitations and reported comparisons may vary depending on the marker model employed (Kanko, E. K. Laende, *et al.*, 2021; D'Souza, Siebert and Fohanno, 2024; Wishaupt et al., 2024; Greaves et al., 2025; Kearney et al., 2025). This study included only typically developing children performing self-selected gait trials in a single gait laboratory. Findings may therefore not generalise to children with pathological gait, more complex movement tasks, or different laboratory and camera configurations. Only left-sided gait cycles were analysed, and potential side-specific measurement effects were therefore not assessed. Averaging repeated gait cycles provided a representative participant-level waveform and reduced the influence of stride-to-stride variability, however, this may attenuate trial-specific inter-version differences where the direction or magnitude of the offset varies between individual cycles. Camera setup and configuration may influence pose estimation and tracking, with recent evidence showing that camera positioning can affect kinematic outputs (Kwak et al., 2026) and lighting may affect measurements in the frontal and transverse planes (Thomas et al., 2026). Therefore, the findings of the present study should be considered specific to the capture configuration and laboratory conditions used and caution is required when generalising software-version effects across laboratories. Participants were assessed barefoot only, whereas clinical gait analysis may also include shod walking and assessment with assistive devices such as ankle-foot orthoses. These conditions may alter both gait biomechanics and the visual characteristics of the distal lower limb and therefore inter-version differences may not be identical across assessment conditions. Participants were also assessed in relatively minimal clothing because data were collected concurrently with marker-based motion capture. Previous work suggests that Theia3D derived kinematics are relatively robust to differences between sports and everyday clothing (Keller et al., 2022). However, clothing can alter the visual features available for pose estimation and it is unknown whether clothing condition interacts with software-version effects. The inter-version differences observed here therefore may not be identical when participants are assessed in less restrictive clothing.

## 5. Conclusion

This study demonstrates that successive updates to Theia3D introduce measurable changes in lower-limb kinematics across joint levels and planes of motion, with the largest modifications observed between v2022 and v2023. Changes across versions were not consistent in pattern, with some variables reverting towards earlier outputs. Variability in transverse plane hip kinematics highlights the ongoing challenge of accurately estimating axial rotations using pose estimation approaches. Software version therefore represents an important methodological factor that can influence kinematic outcomes. Clear reporting of software version is essential in research, clinical, and applied settings, and comparisons across versions should be undertaken with caution. Where consistency is required, reprocessing using a single software version is recommended. Version updates may also present challenges for longitudinal analyses and sensitivity analyses may be considered when reprocessing is not feasible. Finally, documented details of version changes by manufacturers and further research is needed to establish the clinical impact of inter-version differences.

## CRediT authorship contribution statement

**Joel Kearney:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Henrike Greaves:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Mark A. Robinson:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Data curation, Conceptualization. **Gabor J. Barton:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Thomas D. O'Brien:** Supervision, Funding acquisition, Conceptualization. **Karl C. Gibbon:** Writing – review & editing, Validation, Supervision, Software, Methodology, Funding acquisition, Conceptualization. **Richard J. Foster:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: RJF and KG are currently funded by Theia Markerless Inc. for a separate project based at Liverpool John Moores University. This project was not funded by Theia Markerless Inc. No other personnel or resources from Theia Markerless Inc. were involved in the generation or interpretation of these data or manuscript. No other authors have conflicts to disclose.

## Appendix A. Supplementary data

Supplementary Figure 1**:** Mean and 1SD kinematic waveforms for trunk, pelvis, hip, knee, and ankle across the gait cycle for Theia3D versions 2022 (black), 2023 (blue) 2024 (red) and the CGM1.1 model (green). Supplementary Figure 2**:** Mean Theia3D and CGM1.1 version difference curves across the gait cycle for trunk, pelvis, hip, knee, and ankle kinematics. Differences are shown for sequential comparisons (CGM vs 2022; CGM vs 2023 and CGM vs 2024). Positive and negative values indicate the direction of offset between versions. Blue line represents the difference curve between CGM and v2022. Red line represents the difference curve between CGM and v2023. Yellow line represents the difference between CGM and v2024. CGM1.1 data were collected synchronously during the same experimental sessions and originate from the larger study reported by Kearney et al. (2025). The marker-based data shown here corresponds to the same 16 participants

included in the present analysis and are provided for contextual comparison only. Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2026.113639.

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