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Comparison of Theia3D and the conventional gait model in typically developing children and adults in a clinical gait laboratory

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ABSTRACT

Marker-based motion capture is the clinical standard for gait analysis, requiring precise marker placement on anatomical landmarks. This process is time-consuming and prone to human error. Theia3D, a markerless system using machine learning and neural networks, tracks features from 2D video to produce 3D motion analysis, but has yet to be clinically validated, and its use for children is minimal. This study compared markerless system (Theia3D) joint tracking with currently the most widely-used marker-based model in clinical gait analysis (Conventional Gait Model, CGM1.1) in typically developing children and adults. Twenty-three children and 34 adults underwent gait assessments at Alder Hey Children's Hospital, where data from both systems were collected synchronously. Kinematics, kinetics and segment lengths were calculated from both systems. Model differences were quantified using pairwise root mean square deviations (RMSD) during phases that were statistically significantly different as determined by statistical parametric mapping. Segment length differences produced by each model were assessed by mean difference, standard error of the mean and minimal detectable change. Significant differences were observed across the gait cycle in all but one joint levels and planes, with RMSDs up to 8.5° in the sagittal plane, 5.3° in the frontal plane and 10.2° in the transverse plane. Theia3D produced larger peak knee moments in the sagittal and frontal plane compared to the CGM1.1 model and produced shorter segment lengths. This study shows the potential of the developing Theia3D's software in clinical gait analysis with children and adults but emphasises the need for further investigations across populations.

1. Introduction

The requirement for accurate biomechanical data is a necessity for clinical gait analysis, enabling appropriate and informed treatment decisions for individuals with movement disorders (Armand et al., 2016). Marker-based motion capture remains the clinical standard for three-dimensional (3D) gait analysis, but there are several well-known limitations. Markers are placed on the skin to represent specific anatomical landmarks (Mündermann et al., 2006), yet movement of skin and soft tissue (e.g. muscle and fat) can result in inaccuracies in representing the underlying bone positions (Reinschmidt et al., 1997), necessitating skilled clinicians to ensure accurate marker placement. Standard marker-based procedures can take up to two hours and require minimal clothing, patient cooperation, and the ability to stand still and walk in a representative manner, which may be especially challenging for children with intellectual disabilities (Hallemans et al., 2019). Marker-based motion capture may therefore not be appropriate for all children requiring gait analysis. Markerless motion capture technologies have been developed to address many of the practical and technical challenges associated with marker-based systems and to reduce data collection time (Ito et al., 2022; Wade et al., 2022). These technologies may offer a viable alternative in populations for whom marker-based analysis is not feasible.

Markerless motion capture technology has advanced significantly, with various approaches used to track human movement. This included single camera pose estimation approaches such as OpenPose (D'Antonio et al., 2020) and depth cameras such as Microsoft Kinect (Pfister et al., 2014). While less time-consuming, single camera pose estimation methods are typically constrained to 2D tracking and are susceptible to occlusion errors (Clark et al., 2019). More recent developments leverage

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position and orientation (pose) estimation algorithms based on machine learning techniques, particularly convolutional neural networks trained on large datasets to identify specific features in images and track pixel movement (Wade et al., 2022). Typically, these pose estimation methods identify proximal and distal joint centre locations, supporting 2D tracking in the sagittal and frontal planes (Wade et al., 2022). To achieve full six Degrees of Freedom (DoF), a third point on the segment is required, as is also the case with marker-based systems. Advances such as multi-camera configurations, enhanced feature identification, and larger labelled training datasets now enable 3D joint centre estimations in markerless motion capture (Kanko et al., 2020). For example, Theia3D (Theia Markerless, Inc., Canada) requires a minimum of six cameras to optimise joint visibility and feature detection. Its neural networks apply consistent anatomical rules across participants, thereby reducing potential human error (Kanko et al., 2020). These developments may increase the clinical appeal of markerless systems, particularly for patients such as young children or those with sensory or intellectual impairments, who may not tolerate physical markers (Hallemans et al., 2019).

To date, only one study has compared marker-based and markerless kinematics exclusively in typically-developing children during overground gait (Wishaupt et al., 2024), reporting that the greatest differences exist in the transverse plane, along with systematic sagittal plane offsets. Further comparisons involving adults and a mixed cohort of children and adults reported similar findings (Kanko et al., 2020; Song et al., 2023; D'Souza et al., 2024; Wishaupt et al., 2024). These studies employed a range of different marker-based models, including custom configurations (Kanko et al., 2020; Song et al., 2023), Plug-in-Gait (Wren et al., 2023), Human Body Model (HBM) (Wishaupt et al., 2024), and CAST (D'Souza et al., 2024), several of which are not typically used in clinical gait analysis. Notably, no comparison has yet been made between Theia3D and the CGM1.1 model, which is one variant of the most commonly used CGM models in clinical services (Armand et al., 2024). Joint moments and powers during overground walking have been reported using both the CAST and markerless model in a mixed cohort of children and adults. Joint moments visually presented similarly; however, higher peak frontal plane hip and knee moments were observed in Theia3D (D'Souza et al., 2024). Segment lengths influence joint centre estimations and, consequently joint moment calculations, which are critical for clinical decision-making. Segment length differences are expected between marker and markerless-based systems due to their distinctive model definitions. Markerless-derived thigh and shank segment lengths have been shown to vary by ~4 cm depending on clothing conditions during walking, squatting, and hopping (Ito et al., 2022) and by 1–7 % depending on clothing type (Augustine et al., 2025). However, no study has directly compared segment lengths between marker-based and markerless models in children. As an essential first step, it is necessary to evaluate differences between systems in typically developing children and adults before extending validation to pathological populations. Understanding joint kinematics, kinetics, and the anatomical assumptions underlying segment definitions in these groups is critical for establishing confidence in markerless gait analysis for future clinical use. Based on prior validation work, we hypothesised that statistically significant between-system differences would be detected by statistical parametric mapping (SPM), particularly in the frontal and transverse planes where measurement reliability is typically lower, while sagittal plane differences would largely remain within clinically acceptable thresholds ($\leq 5^{\circ}$). For joint kinetics, we expected waveform shapes to be similar across systems, but with differences in magnitude at specific phases of the gait cycle, especially in the frontal plane. For segment lengths, we anticipated systematic differences between models, with mean offsets less than 20 mm, consistent with prior reports of clothing effects. To test these hypotheses, the present study directly compared kinematic, kinetic, and segment length outputs from markerless (Theia3D) and marker-based (CGM1.1 model) gait analysis in typically developing children and adults.

2. Methods

2.1. Participants

Thirty-four healthy adults (22 female, 12 male, age = 36.5 ± 12.2 years, height = 170.8 ± 8.6 cm, mass = 72.5 ± 17.8 kg) and 23 typically-developing children (15 female, 8 male, age = 9.9 ± 3.2 years, height = 142.5 ± 18.4 cm, mass = 36.9 ± 13.2 kg) 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 recruited from hospital staff and their family members; all adults were healthy and all children typically developing, and all participants were free from any injury or condition that would affect their walking.

2.2. Set up and collection procedure

Ten Qualisys Miqus video cameras (1920 × 1080 resolution, RGB video) and twelve Qualisys Arqus marker-based cameras (Qualisys AB, Gothenburg, Sweden) captured synchronously at 100 Hz. Four AMTI Optima-MMS force plates (MMS400600) sampling at 1000 Hz were used to collect ground reaction forces. The cameras were positioned to provide both sagittal and frontal plane views, focused on the centre of the laboratory, at a height of approximately 2 m above the ground, and oriented to capture gait in both walking directions. Both camera systems were connected to the same instance of Qualisys Track Manager for synchronisation and were calibrated simultaneously, resulting in a shared global reference frame. Each participant was asked to walk until at least five kinematic trials were conducted. This study was approved in the form of a local clinical audit (audit number: 6921) from the Clinical Audit Team/Governance and Quality Assurance Interim Site at Alder Hey Children's NHS Foundation Trust on 19/07/2023. Written informed consent was obtained from each participant or their legal guardian.

Participants wore minimal tight-fitting clothing so that retroreflective markers could be placed directly onto the skin where possible in accordance with the CGM1.1 model (Leboeuf et al., 2019). Specific colours or contrast of top and bottom clothing items were not controlled for in this study. Minor changes to marker placement can lead to differences in coordinate system orientation and, consequently, errors in knee abduction/adduction and internal/external rotation angle curves. This is known as the kinematic 'cross-talk' effect. To minimise this effect in the marker-based assessment, one static and one walking trial were collected first and processed to evaluate the varus/valgus profile of the marker-based assessment. If the knee varus/valgus profile exhibited crosstalk with knee flexion, the medial or lateral knee marker was adjusted and a new static trial was collected (Kainz et al., 2016). No separate static calibration was required for markerless data analysis.

2.3. Data analysis

Video data were processed using Theia3D (v2023.1.03161, Theia Markerless Inc., Kingston, Ontario, Canada). Theia3D applies a deep neural network to identify salient anatomical features across multiple video frames, which are then used to reconstruct 3D pose and estimate joint centres and segment orientations within a full-body inverse kinematics model (pelvis: six degrees of freedom; thorax, hip, knee, ankle: three degrees of freedom each). Theia3D outputs these data as C3D files containing joint centre positions, segment orientations, and kinematics. These files were imported into Visual3D (v2024.7.2, HAS Motion, Kingston Ontario, Canada), where two skeletal models were created: one that tracked the markerless pose matrices automatically generated when Theia3D data were loaded, and a second that tracked the marker trajectories, manually defined using the conventional CGM1.1 marker set (Image 1). This approach ensured that kinetic calculations and post-processing were performed consistently across both marker-based and

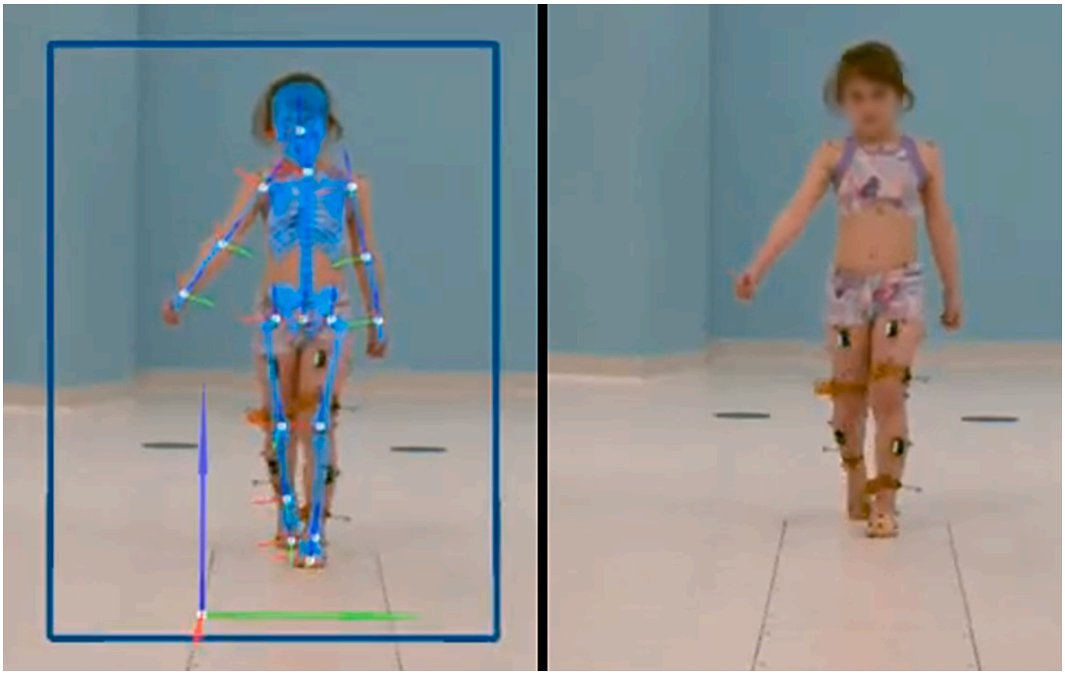

Image 1. Simultaneous marker-based and markerless motion capture of a child participant during walking. Left: Theia3D skeletal overlay illustrating estimated segment poses and joint centre locations generated from video using proprietary deep learning algorithms. Right: The same frame shown without overlay, displaying the Conventional Gait Model marker set placed on anatomical landmarks. Parental consent was provided for use of this image.

markerless datasets. No filtering was applied during Theia3D processing (i.e. default GCVSPL not used). Marker-based and markerless kinematic data were exported unfiltered and a 6 Hz low-pass Butterworth filter was applied in Visual3D. For the marker-based trials, virtual foot markers were generated in Visual3D using the heel and toe (dorsal aspect of the 2nd metatarsal head) targets to define the proximal and distal ends of the foot. These additional landmarks were derived directly from the physical markers and offset in the foot coordinate system to ensure correct alignment of the foot segment. Because Theia3D does not output raw marker trajectories, the foot segment definition cannot be adjusted in the same way within Visual3D, and the Theia3D segment definitions were used as provided. The Visual3D default Bell and Brand equation was used for hip joint centre estimation for marker-based data (Bell et al., 1989). For consistency with standard clinical gait lab procedures where kinetic or kinematic algorithmic-based gait events are often problematic in children and specific pathologies, gait events were defined manually by the clinician. All clinicians' processing data had passed a repeatability assessment to ensure consistency in gait event detection. Heel strike was defined as the first instance of foot contact with the force plates where the GRF vector was visible, and by the first frame where the limb is not moving forwards or downwards and is on the ground when there was poor or no contact with the force plates. Foot-off was defined as the first frame when the GRF is not visible during clean foot strikes, and the first frame where the GRF stops moving away from foot coming off the ground and stays under the opposite foot for not clean contacts, and finally the first frame where the ankle stops rotating before the foot starts to move off from the ground when there was no contacts with a force plate. Events were frame-matched between systems to ensure consistency of events for both markerless and marker-based trials. As all participants were without pathology, only left-sided kinematics and kinetics were presented.

Thorax, pelvis, hip, knee and ankle kinematics were calculated across all three planes, excluding knee angle in the transverse plane, while including foot progression. Joint kinetics included the internal hip, knee and ankle sagittal and frontal plane moments, and sagittal hip, knee and ankle powers. Joint moments were normalised to body mass and all data were normalised to 100 % of the gait cycle. A one-dimensional Statistical Parametric Mapping (1D-SPM) paired *t*-test was performed using the *spm1d* package (Pataky, 2010) in MATLAB (R2023a, The MathWorks Inc.) to determine the differences within the gait cycles between both systems. A statistically significant difference was determined if the SPM{t} curve exceeded the critical threshold with alpha at 0.05. Between-system differences were further evaluated by calculating mean differences with 95 % confidence intervals (CIs), using the paired confidence interval function in spm1d ($\alpha = 0.05$). To allow direct comparison to previous studies root mean square differences (RMSD) were calculated for the extent of supra-threshold clusters; the period/s of the gait cycle when there were statistical differences between kinematic or kinetic curves. The significantly different parts of the kinematic and kinetic curves between systems were calculated between the corresponding pairwise gait curves of both systems for each participant then averaged across all.

Segment lengths were calculated for both marker-based and markerless trials as the distance between the distal and proximal end positions for thorax, thigh, shank and foot, while hip widths were the distance between left and right hip joint centres over the entire gait cycle. A positive mean difference shows the CGM1.1 (marker based) segment lengths were greater. Standard Error of the Mean (SEM), 95 % Confidence Intervals and Minimal Detectable Change (MDC) were calculated as means of reliability and comparison of segment lengths between systems.

3. Results

3.1. Kinematics

3.1.1. Sagittal plane

The markerless system showed significantly greater thorax anterior tilt (RMSD in children = 3.3°, RMSD in adults = 2.3°-2.4°), less pelvis anterior tilt (RMSD in children = 7.8°, RMSD in adults = 5.0°) and greater knee flexion (RMSD in children = 6.7°, RMSD in adults = 8.5°) throughout the entire gait cycle. In terminal stance phase, children and adults exhibited significantly greater hip extension (RMSD of 5.2° and 4.3°, respectively) (See Figs. 1 and 2). The markerless system showed

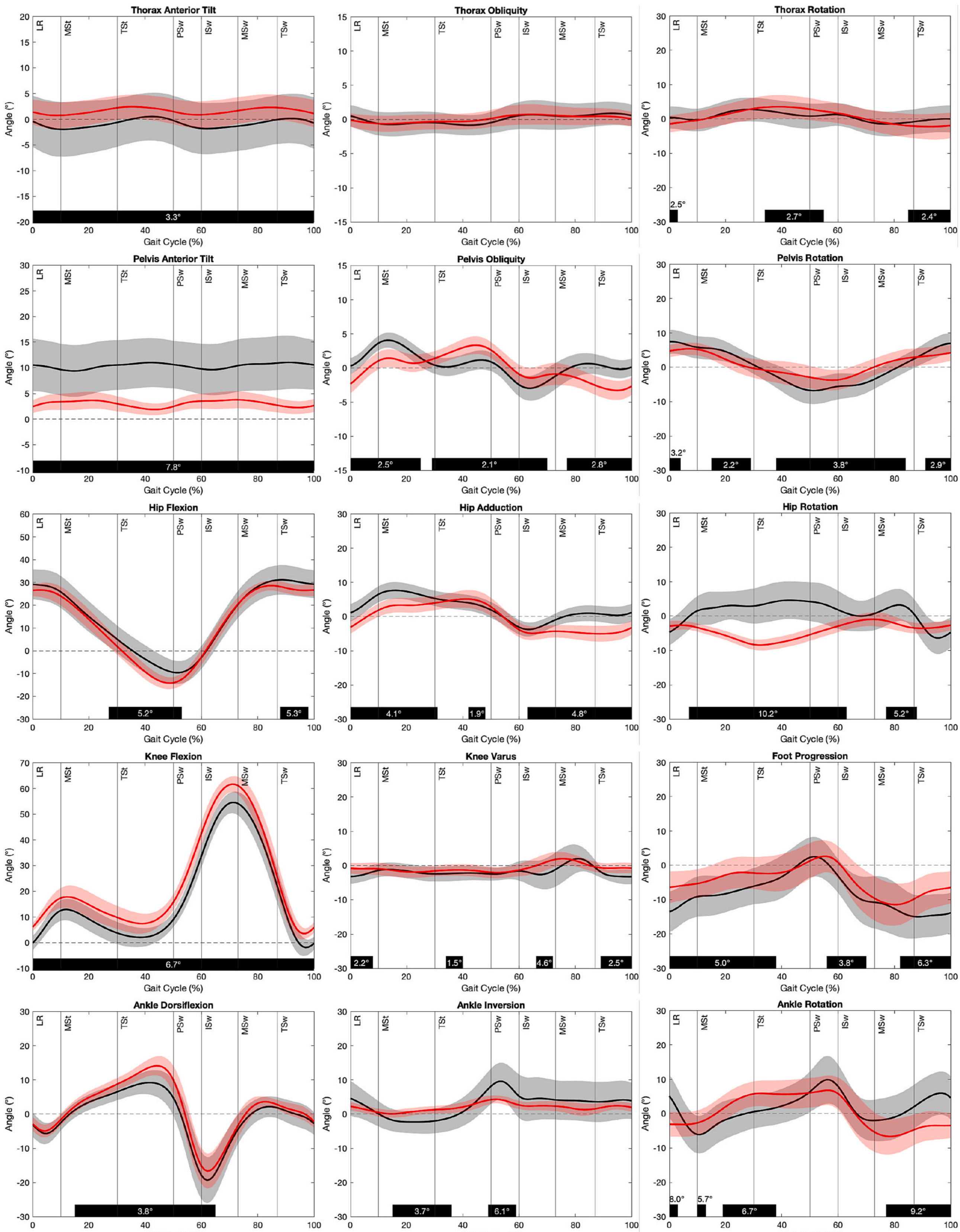

Fig. 1. Thorax and lower body kinematics of typically developing children (±1SD) for both marker-based (black) and markerless (red). Horizontal black bars and accompanying RMSD values represent phases of the gait cycle where 1D-SPM analysis identified a significant difference between models and the magnitude of that difference. LR = loading response, MSt = midstance, TSt = terminal stance, PSw = pre swing, ISw = initial swing, MSw = mid swing, TSw = terminal swing.

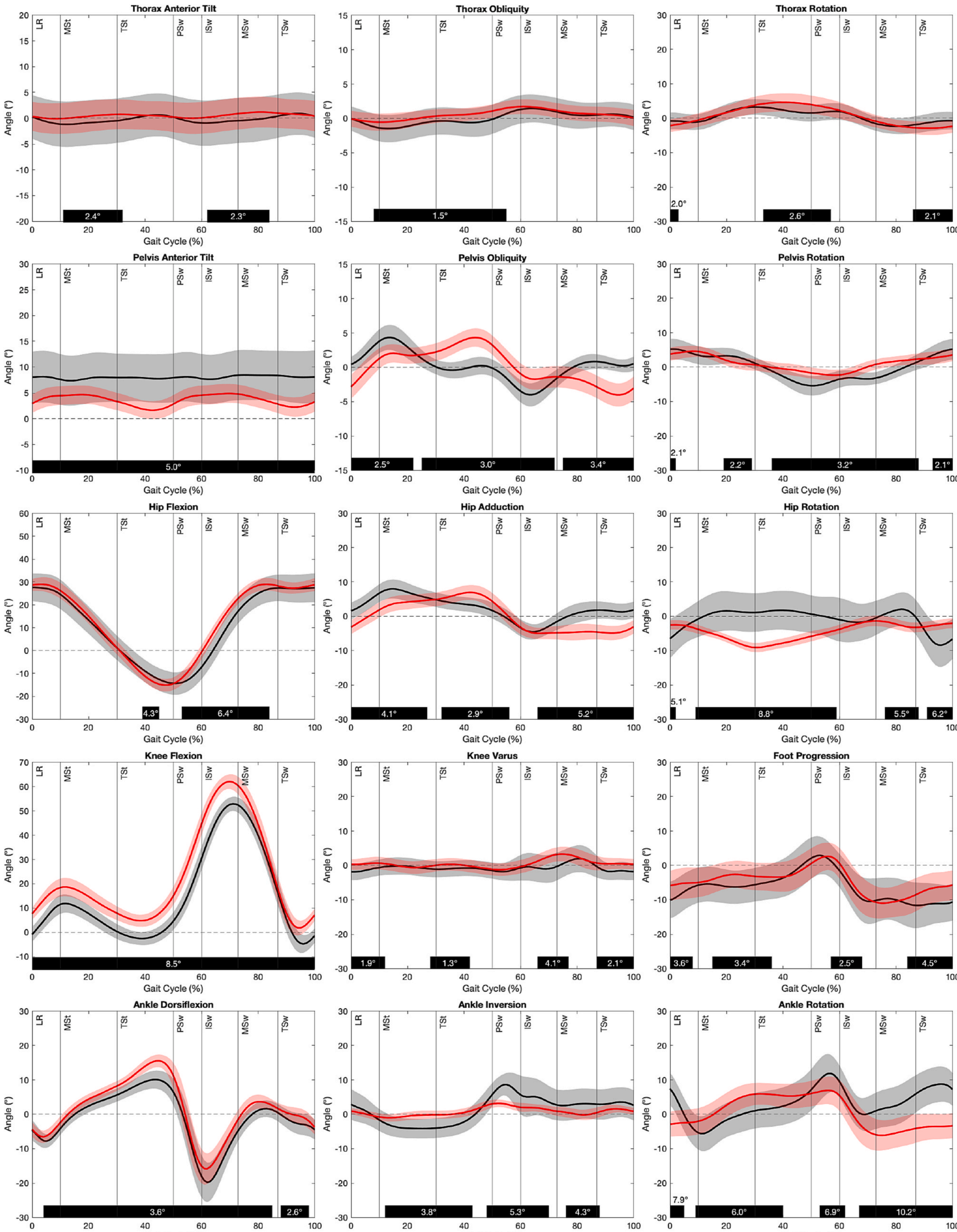

Fig. 2. Thorax and lower body kinematics of healthy adults (±1SD) for both marker-based (black) and markerless (red). Horizontal black bars and accompanying RMSD values represent phases of the gait cycle where 1D-SPM analysis identified a significant difference between models and the magnitude of that difference. LR = loading response, MSt = midstance, TSt = terminal stance, PSw = pre swing, ISw = initial swing, MSw = mid swing, TSw = terminal swing.

significantly greater dorsiflexion during stance for children (RMSD = 3.8°), but a systematic offset towards greater dorsiflexion during stance and less plantarflexion during swing for adults (RMSD = 3.6°). Mean differences with 95 % confidence intervals are provided in Supplementary Materials, illustrating the magnitude and precision of between-system differences (see Supplementary Materials 1).

3.1.2. Frontal plane

Significant differences were observed across most joint levels at different phases of the gait cycle in the frontal plane, with RMSD ranging between 1.5° – 6.1° in children and 1.3° – 5.3° in adults. Notably, during swing the markerless system exhibited greater hip abduction in both children (RMSD = 4.8°) and adults (RMSD = 5.2°).

3.1.3. Transverse plane

Significant differences between systems were evident across the stance and swing phase in children and adults. The markerless system showed significantly greater external hip rotation across stance and pre-

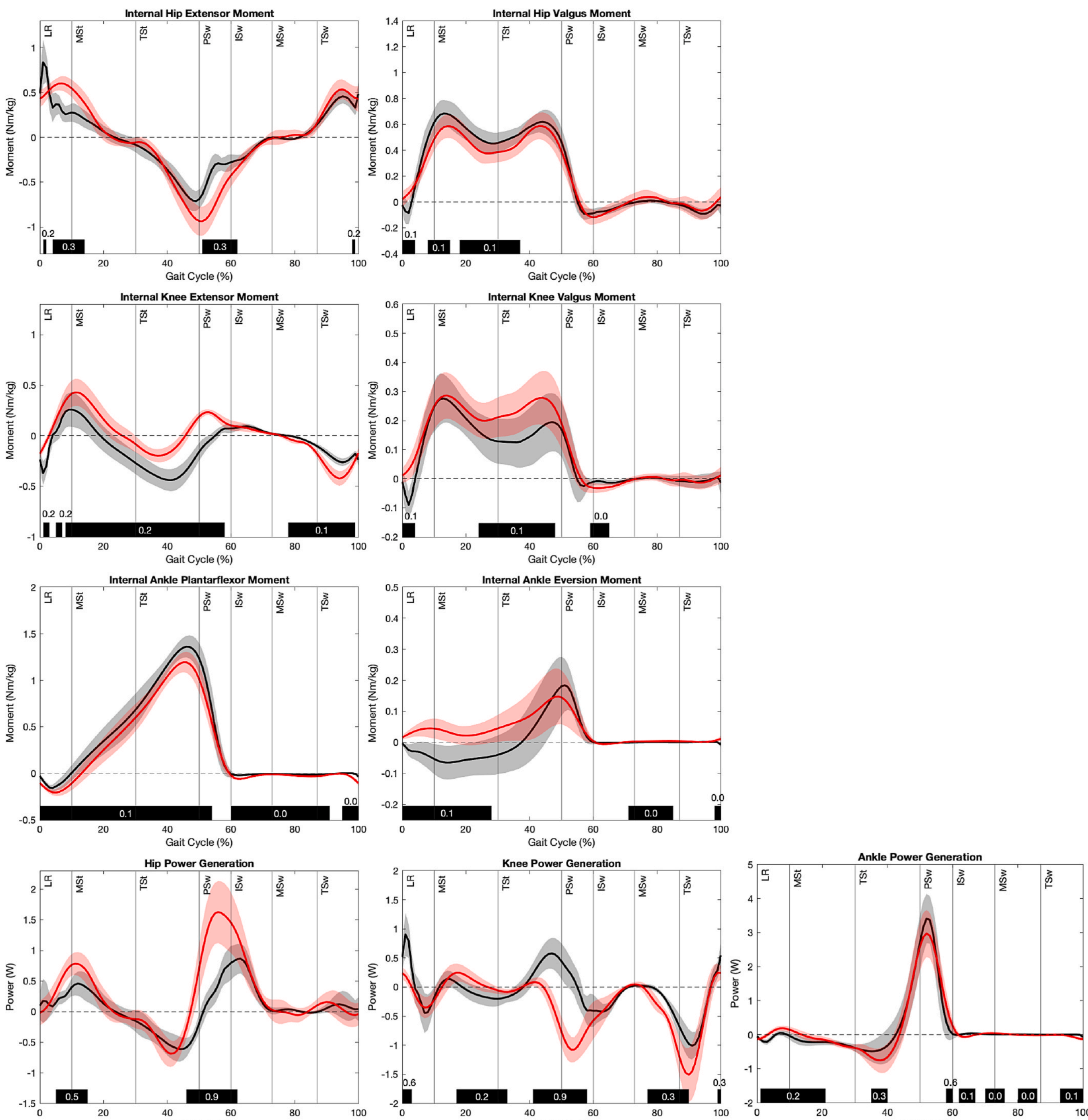

Fig. 3. Hip, knee and ankle moments and powers of typically developing children (plus/minus 1SD) for both marker-based (black) and markerless (red). Horizontal black bars and accompanying RMSD values represent phases of the gait cycle where 1D-SPM analysis identified a significant difference between models and the magnitude of that difference. LR = loading response, MSt = midstance, TSt = terminal stance, PSw = pre swing, ISw = initial swing, MSw = mid swing, TSw = terminal swing.

swing (RMSD in children = 10.2°, RMSD in adults = 8.8°) and external ankle rotation between mid and terminal swing (RMSD in children = 9.2°, RMSD in adults = 10.1°).

3.2. Kinetics

Nine children and three adults were excluded from the kinetic analysis due to incomplete full foot contact with the force platforms during the gait trial. In both children (Fig. 3) and adults (Fig. 4), the markerless system showed a significantly greater knee extensor moment across the stance phase (RMSD of 0.2Nm/kg and 0.3Nm/kg, respectively). Ankle plantarflexion moment was significantly less for children throughout the stance phase (RMSD = 0.1Nm/kg) but not adults. The markerless system exhibited significantly greater hip power generation during terminal stance and pre-swing for both children (RMSD = 0.9 W) and adults (RMSD = 0.7 W). The markerless system exhibited knee power absorption during terminal stance and pre-swing, but the marker system exhibited knee power generation, for both children (RMSD = 0.9 W) and adults (RMSD = 1.0 W). Mean differences with 95 % confidence intervals are provided in Supplementary Materials, illustrating the

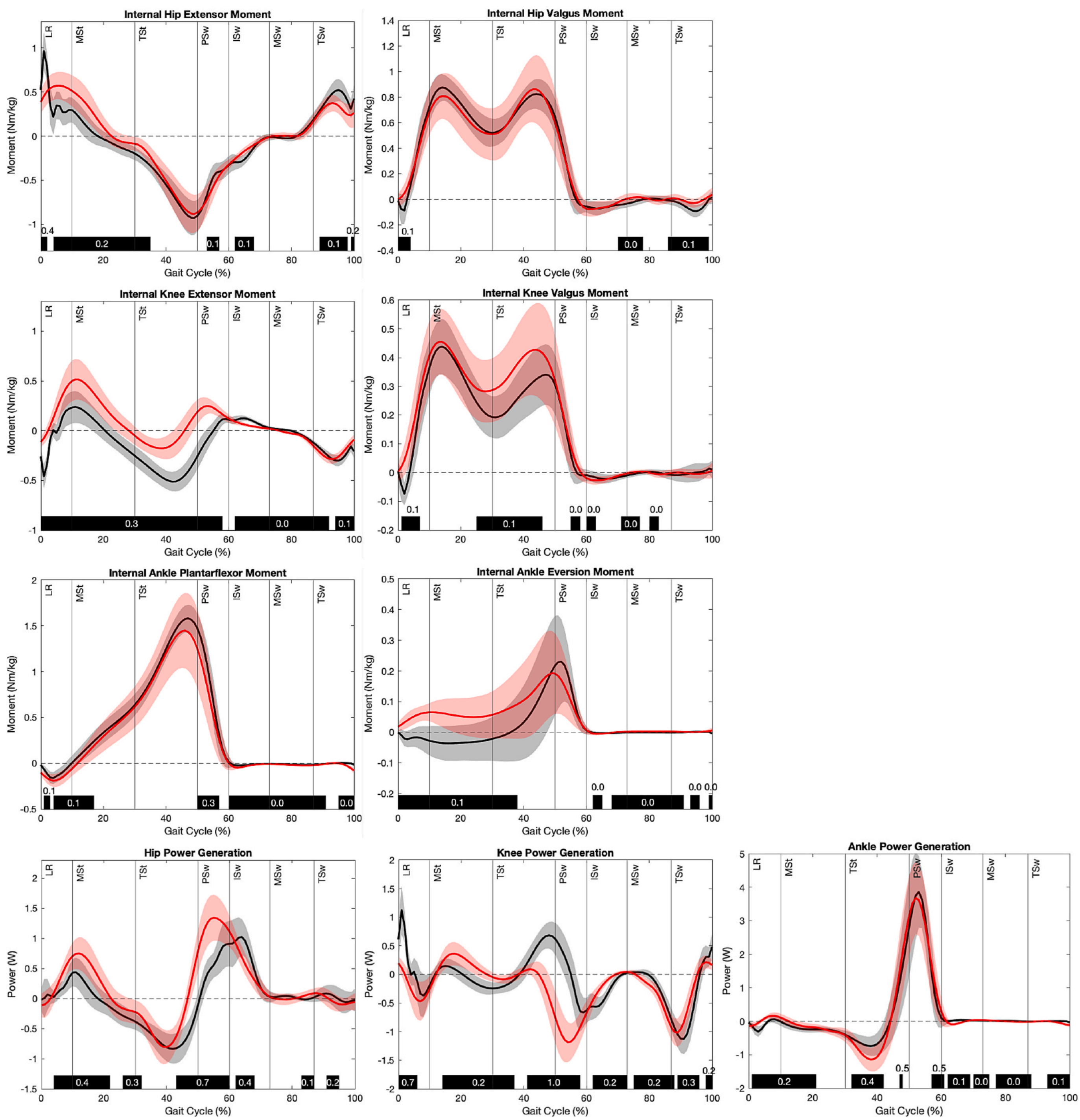

Fig. 4. Hip, knee and ankle moments and powers of healthy adults (plus/minus 1SD) for both marker-based (black) and markerless (red). Horizontal black bars and accompanying RMSD values represent phases of the gait cycle where 1D-SPM analysis identified a significant difference between models and the magnitude of that difference. LR = loading response, MSt = midstance, TSt = terminal stance, PSw = pre swing, ISw = initial swing, MSw = mid swing, TSw = terminal swing.

magnitude and precision of between-system differences (see Supplementary Materials 1).

3.3. Segment Lengths

The marker-based system produced longer segment lengths than the markerless system for both children and adults, except for the thorax in children (Tables 1 and 2). The greatest difference between systems was reported for inter-hip width (18 mm in children, 17 mm in adults). The thigh and foot segment length differences were greater in children (thigh = 10 mm, foot = 11 mm) compared to adults (thigh = 4 mm, foot = 8 mm).

4. Discussion

This study provides a detailed comparison of marker-based and markerless gait analysis in typically developing children and adults within a clinical gait laboratory setting. The markerless system produced significantly different joint angles, moments and powers compared to the marker-based system across most joint levels and planes of motion, particularly during mid to late stance. Segment lengths were also underestimated by the markerless model. Taken together, these findings provide mixed support for our hypotheses. As expected, significant between-system differences were detected by SPM across all planes of motion. While many differences fell within commonly cited clinical thresholds (≤5°), some sagittal and transverse plane differences exceeded this threshold, whereas most frontal plane differences remained below it. Joint kinetics showed broadly similar waveform shapes but with differences in magnitude at specific phases of the gait cycle, consistent with our expectations. Segment length differences were systematic and typically modest (<20 mm), in line with our hypothesis, although a larger inter-hip width difference was observed in children. These findings are discussed in more detail below.

The systematic offset observed in sagittal plane kinematics aligns with previous literature on markerless motion capture (Kanko et al., 2020; Song et al., 2023; D'Souza et al., 2024; Wishaupt et al., 2024). Previous reports in children present offsets at the thorax (9.2°), pelvis (8.9°) and hip (6.8°) (Wishaupt et al., 2024). We show offsets in children at the thorax (3.3°), pelvis (7.8°) and knee (6.7°), and in adults at the pelvis (5.0°) and knee (8.5°) across the entire gait cycle which likely reflect different model definitions (Kanko et al., 2020). We observe a more neutral pelvic tilt across both groups with Theia3D which aligns with previous research (Song et al., 2023; D'Souza et al., 2024; Wishaupt et al., 2024).

The greater external hip rotation observed during stance and preswing in both groups supports findings from Kanko et al. (2020) and Wishaupt et al. (2024). However, differences were not consistently distributed across groups or time points. In hip flexion, children exhibited a greater RMSD (5.2°) throughout terminal stance, while adults exhibited a lower RMSD (4.3°) over a shorter period of the same phase. Hip extensor moments did not differ in either group during this phase, despite the observed kinematic discrepancies. Tracking axial hip rotation is challenging due to difficulty identifying the underlying bone. Proximal locations for marker placement like the anterior superior iliac spine are often problematic due to soft tissue or high BMI (Camomilla et al., 2017). Also, hip rotation in non-pathological gait is minimal and so very little displacement of markers on the thigh is observed. Marker-based solutions often require complex marker sets or functional calibration, which may lengthen data collection while markerless faces similar challenges when tracking axial rotations including occlusion and limited clothing or skin texture under poor lighting or camera setup. Importantly, however, neither system can be considered error-free: studies using biplanar videoradiography have demonstrated substantial errors in marker-based estimates of joint kinematics (Kessler et al., 2019; D'Isidoro et al., 2020). Such direct validation methods provide valuable insight into the true accuracy of motion capture systems, although their invasive nature and limited field of view constrain their widespread use in clinical gait analysis. As Theia3D's neural network continues to be refined with larger and more diverse training datasets, improvements in hip rotation tracking may emerge. Current inconsistencies may also result from feature identification errors, the network's limited exposure to children, camera setup height, and greater variability of children's gait. Given the clinical importance of axial rotations, further research is needed to benchmark both marker-based and theia markerless estimates against more direct imaging methods such as biplanar videoradiography, which can provide a more accurate reference for evaluating system error.

Markerless-derived joint moments showed some visual similarities to marker-derived moments but with greater peak knee extensor moment in loading and midstance, complementing the observations made by D'Souza et al. (2024). The definition of the hip joint centre is known to propagate to hip and knee kinetics because of an altered alignment and motion of the thigh segment (Stagni et al., 2000), and thus is an expected outcome of comparison between two different systems and their underlying kinematic models. It should be acknowledged that hip joint centres were estimated using the Visual3D default Bell and Brand approach (Bell et al., 1989). Alternative methods, such as functional calibration approaches (e.g., SCoRE (Ehrig et al., 2011), Gillette (Schwartz and Rozumalski, 2005)), may influence joint centre locations and derived kinematics and kinetics. While valuable, regression methods remain popular in clinical gait laboratories, and our use of the Bell and Brand approach reflects current practice at our clinical gait laboratory. The differences in joint centre locations will subsequently affect the moment arms, potentially resulting in the deviations between systems observed here. This may further result in misinterpretation of muscle force contributions around the knee. Small RMSDs and similar waveforms patterns for kinetics may appear promising, but we still lack kinetic reference values to determine acceptable thresholds for clinical interpretation. Comparison against a true gold standard would enhance the understanding of how close Theia3D's HJC prediction is to ground truth, but establishing norms from the system using healthy participants provides value for comparison if pathological gait data is collected.

Table 1
Children segment length mean differences (in mm), SD, SEM, 95% Confidence Intervals and Minimal Detectable Change (MDC) for thorax, hip widths and right-sided lower limb 3D segment lengths from marker-based and markerless systems.

Segment Length	Thorax	Hip Width	Thigh	Shank	Foot
Mean diff. (mm)	−5.99	17.92	10.22	9.92	10.63
SD	0.020	0.007	0.011	0.007	0.005
SEM	0.004	0.001	0.002	0.002	0.001
95 % CI	−0.014, 0.002	0.015, 0.021	0.006, 0.015	0.007, 0.013	0.009, 0.013
MDC	0.05	0.02	0.03	0.02	0.01

Table 2
Adult segment length mean differences (in mm), SD, SEM, 95% Confidence Intervals and Minimal Detectable Change (MDC) for thorax, hip widths and right-sided lower limb 3D segment lengths from marker-based and markerless systems.

Segment Length	Thorax	Hip Width	Thigh	Shank	Foot
Mean diff. (mm)	4.57	17.25	4.26	14.75	7.63
SD	0.029	0.012	0.013	0.007	0.031
SEM	0.005	0.002	0.002	0.001	0.005
95 % CI	−0.005, 0.014	0.013, 0.021	0.000, 0.009	0.012, 0.017	−0.003, 0.018
MDC	0.08	0.03	0.04	0.02	0.09

Segment length differences further reflect the distinct model definitions used in each system. Mean differences below 10 mm were observed at the trunk and shank in children, and trunk, thigh and foot in adults. One possible explanation is that Theia3D internally scales its biomechanical model to participant stature, although the specific procedures are not disclosed and therefore this remains speculative. The larger inter-hip width difference (~17 mm) observed in children, relative to pelvic size, contributes new insight into markerless measurements in paediatric populations, an underreported area. Previous comparisons found that clothing can influence markerless thigh segment lengths by up to ~30 mm (Ito et al., 2022; Augustine et al., 2025). It is important to note, however, that marker-based systems are not a true gold standard for estimating segment lengths, as these too are subject to error. We therefore do not interpret our results as definitive over- or underestimation by Theia3D, but rather as differences relative to our current clinical standard, which is the reference model against which new methods must initially be validated in our lab. Further work comparing Theia3D outputs with imaging-based approaches such as DEXA or EOS imaging would provide a more accurate benchmark, and the establishment of normative databases in markerless systems will be essential for their eventual use in clinical populations with gait pathology.

RMSD values below 2° across the gait cycle are often cited as clinically acceptable for kinematic variation within a single measurement system (Stewart et al., 2023), and a 5° threshold has been proposed in relation to inter-rater reliability (McGinley et al., 2009; Wilken et al., 2012). However, these pragmatic benchmarks should not be interpreted as absolute standards of accuracy, since marker-based system themselves are subject to errors of this magnitude and greater, arising from soft tissue artefact and marker misplacement (Leboeuf et al., 2023), In this context, differences exceeding 2° between marker-based and markerless systems do not necessarily imply inaccuracy of the markerless system, but instead may reflect the known limitations of both approaches. Our results indicate that a substantial proportion of between-system differences fell within these commonly cited benchmarks, while others exceeded them at specific joints and phases of the gait cycle. These findings suggest that offsets are expected when comparing systems with fundamentally different segment definitions, and interpretation should be anchored to the recognition that neither system provides a true gold standard. Importantly, our results highlight the promise of Theia3D as a clinically applicable tool and the need for cautious interpretation of between-system differences until consistency is confirmed in pathological populations.

Additional outcome measures commonly used in clinical gait analysis, such as the Gait Deviation Index, have been shown to yield lower scores when derived from markerless data in children with cerebral palsy, whereas the Gait Variability Index showed no difference between systems in the same study (Poomulna et al., 2025). Although such metrics are rarely used in isolation, these findings suggest that outputs from markerless systems may systematically differ and must be interpreted with care. RMSD alone may not sufficiently indicate whether a difference is clinically meaningful, and further work is needed to understand the implications of using markerless versus marker-based data in clinical decision-making.

An additional consideration is the repeatability of data collection across multiple sessions. Marker-based systems are prone to intersession variability due to marker placement differences and associated kinematic cross-talk, which can limit their utility in longitudinal clinical assessments (e.g., pre- vs post-intervention). In contrast, markerless approaches are less affected by these sources of error, as demonstrated by Keller et al. (2022) and recent work by Augustine et al. (2025) on between-session repeatability. This suggests that some of the between-system differences observed in the present study may be less impactful when viewed in the context of repeated clinical testing, where markerless approaches may offer improved reliability over time.

Limitations:

This study has several limitations. Theia3D's training dataset is proprietary, so details of the underlying model are unknown. Diverse age, ethnicity, and BMI in training sets is essential to reduce bias and improve generalisability. Despite this, our findings demonstrate comparable differences in both typically developing children and adults. As a rapidly developing technology, future software updates may enhance feature identification and allow reanalysis of existing data. Users should monitor updates closely (Kearney et al., 2024). A further limitation is the potential influence of visible reflective markers in the video recordings on Theia3D outputs. Previous work has suggested that marker presence may alter markerless segment estimates, likely because the neural network was not trained on such images (Ito et al., 2022), or body images with only shorts and a tight top, walking barefoot. While this effect remains speculative, it should be considered when interpreting direct comparisons between marker-based and markerless systems. The synchronous capture method may have had some confounding effect, as markerless gait analysis aims to reduce unnatural walking patterns caused by markers, and its impact on kinematics remains unknown. In addition, the present study used the CGM1.1 model because it reflects current clinical practice within our laboratory, although newer iterations of the CGM (e.g., 2.6) include updated marker sets and joint centre definitions. Future work will be required to validate Theia3D against these newer models as they are adopted in clinical services. The exact patient and clinician benefit of a markerless clinical gait analysis is still to be established. Since clinical gait analysis is not typically performed on children without pathology, future research must evaluate these technologies in pathological populations.

5. Conclusion

In summary we have shown that Theia3D can provide visually comparable tracking of some joint kinematics and kinetics in healthy adults and TD children, as well as segment lengths within 4–14 mm range. Continued improvements in neural network training may further enhance accuracy. Until further validation studies establish their clinical reliability, users must exercise caution with interpretations. The increasing use of Theia3D presents opportunities to establish normative datasets, promote consistent protocols, and support cross-laboratory validation with specific versions. These steps are essential for developing clinically relevant thresholds supported by empirical evidence and expert consensus. Future research should also investigate Theia3D across various pathologies to assist in the possibility of establishing appropriate application in clinical settings.

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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:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Ornella Pinzone:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **David M Wright:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Karl Gibbon:** Writing – review & editing, Validation, Supervision, 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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2025.112995.

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