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Comparison of Marker-based and Markerless motion capture systems to assess gait kinematics and kinetics in children with Cerebral Palsy

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Abstract:	Cerebral Palsy (CP) is a leading cause of childhood motor disability and is frequently assessed through clinical gait analysis using marker-based motion capture systems. However, these systems present challenges, such as errors regarding marker placement and soft tissue artifact. Markerless systems are a potential alternative that offer practical and technical benefits to perform gait analysis, by using computer vision and deep learning algorithms to overcome those limitations. This study compares markerless (Theia3D) and marker-based motion capture systems assessing gait kinematics and kinetics of fifteen children diagnosed with CP, analyzing the differences between the joint angles, moments and powers. Results indicated consistent waveform and good agreement in sagittal plane kinematics (RMSD < 6.0º), particularly for knee flexion. Nevertheless, hip flexion and pelvic tilt showed systematic offsets, and the transverse plane obtained more inconsistent measurements between the systems (RMSD > 10.0º), except for pelvic rotation. Most significant differences at joint kinetics occurred during swing phase and seem to arise from inconsistent joint center and center of mass estimations. Theia3D exhibits great potential for clinical gait analysis, and results suggest that joint kinematics in the sagittal plane are highly comparable. However, accuracy improvements for estimations in other anatomical planes and regarding joint kinetics are still necessary, especially for the use of this technology in clinical settings involving patients with abnormal gait patterns, such as CP patients.

Dear Editor,

On behalf of my co-authors, I am pleased to submit our manuscript entitled "**Comparison of Marker-based and Markerless motion capture systems to assess gait kinematics and kinetics in children with Cerebral Palsy"** for consideration for publication in *Gait & Posture*.

This study compares markerless and marker-based motion capture systems assessing gait kinematics and kinetics of children diagnosed with cerebral palsy. Our findings show that markerless systems still need accuracy improvements to be used in gait analysis for clinical purposes. We believe these results are of particular interest to the readership of *Gait & Posture* because motion capture systems, especially video and markerless systems, are developing at a very rapid pace, and their use in clinical settings is becoming essential to decision making. It is, therefore, essential to ensure data accuracy.

To our knowledge, this work is innovative, and it has not been published previously nor is it under consideration for publication elsewhere. All authors were fully involved in the study and preparation of the manuscript, and they have read and approved the final version of the manuscript and have agreed to its submission to *Gait & Posture*. R.C. and F.J. contributed with the writing of the original draft, data collection and data processing. F.J. and A.V. contributed with the conceptualization and formal analysis of the data. F.J. contributed with supervision of the work and A.V. contributed with funding acquisition and project administration.

Thank you very much for considering our submission and we look forward to your feedback.

Sincerely,

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HIGHLIGHTS

- Markerless systems show good agreement in sagital kinematics in cerebral palsy gait.
- Transverse plane kinematics still have inconsistent measurements between systems.
- Markerless motion capture exhibits great potential for clinical gait analysis.

TITLE PAGE

Manuscript Title

Comparison of Marker-based and Markerless motion capture systems to assess gait kinematics and kinetics in children with Cerebral Palsy

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Abstract:

Cerebral Palsy (CP) is a leading cause of childhood motor disability and is frequently assessed through clinical gait analysis using marker-based motion capture systems. However, these systems present challenges, such as errors regarding marker placement and soft tissue artifact. Markerless systems are a potential alternative that offer practical and technical benefits to perform gait analysis, by using computer vision and deep learning algorithms to overcome those limitations. This study compares markerless (Theia3D) and marker-based motion capture systems assessing gait kinematics and kinetics of fifteen children diagnosed with CP, analyzing the differences between the joint angles, moments and powers. Results indicated consistent waveform and good agreement in sagittal plane kinematics (RMSD < 6.0º), particularly for knee flexion. Nevertheless, hip flexion and pelvic tilt showed systematic offsets, and the transverse plane obtained more inconsistent measurements between the systems (RMSD > 10.0º), except for pelvic rotation. Most significant differences at joint kinetics occurred during swing phase and seem to arise from inconsistent joint center and center of mass estimations. Theia3D exhibits great potential for clinical gait analysis, and results suggest that joint kinematics in the sagittal plane are highly comparable. However, accuracy improvements for estimations in other anatomical planes and regarding joint kinetics are still necessary, especially for the use of this technology in clinical settings involving patients with abnormal gait patterns, such as CP patients.

Keywords: cerebral palsy, markerless motion capture system, clinical gait analysis, kinematics, kinetics

1. Introduction

Cerebral Palsy (CP) is the most common cause of disability in childhood, affecting approximately 17 million individuals worldwide [1]. It encompasses a group of permanent movement disorders that impact posture and muscle tone due to brain injury occurring between the perinatal and neonatal stages, which are critical phases for brain development [2]. CP results from multifactorial causes, including prematurity, stroke, genetic susceptibility, and infections [3]. However, treatment management is not dependent on the underlying cause [4]. Children with CP often undergo surgery and treatments based on the assessments of their gait pattern using motion capture systems, which provide valuable insights into clinical decision-making [4][5][6]. Through instrumented gait analysis, clinicians examine parameters such as spatiotemporal data, kinematics, kinetics, electromyography, and plantar pressure to better understand the patient's condition and support the treatment planning [7][8].

Marker-based motion capture systems have been the reference method for gait assessment, despite several limitations related to the use of markers [5][8]. These systems require access to a laboratory environment equipped with infra-red cameras, and rely on experts to place the markers, which is a challenging task to perform on clinical patients with anatomical deformities [5][9]. The process is time-consuming, requiring participants to wear minimal clothing which interferes with their natural movement pattern and comfort. A major limitation is soft tissue artifact, which consists of the movement of skin-mounted markers relative to the underlying bones they are intended to track due to skin movement, muscle contraction and inertial effects [10][11][12]. It is the largest source of error of marker-based systems and the extent of its effect depends on the marker location, the activity performed, and individual participant characteristics [10][13][14][15]. Regions with significant adipose tissue, such as the thigh, are more prone to this error [16]. As a result, soft tissue artifacts can lead to inaccuracies in the estimation of biomechanic parameters [17][18].

The development of markerless systems has significant potential to overcome these limitations by using computer vision and deep learning algorithms to estimate anatomic landmarks without the need of markers [19][20]. Theia3D is a commercially available system for markerless motion analysis and its interest in clinical biomechanics is growing [21]. This system uses Convolutional Neural Networks, which were labelled by experts and trained on images of over 500,000 humans, to estimate anatomical landmarks, body segments, and other keypoints [22]. By using video cameras and eliminating the need for marker placement, sessions become significantly faster, reducing patient preparatory time and eliminating other time-consuming tasks [8][21]. Data collection can take less than five minutes to collect ten walking trials [23]. This approach is also more convenient for assessors, as clinical patients may have anatomical deformities which may limit marker placement. Additionally, subjects benefit from greater comfort, as tight-fitting clothing is not required, allowing more natural movement and leading to improved results.

The repeatability and concurrent validity of Theia3D have been investigated in healthy adults and demonstrated that spatiotemporal parameters and joint kinematics in the sagittal plane are similar between the two methods [23][22][9]. More recently, the comparison of the joint kinematics between these two systems has also been conducted in clinical patients [24]. Nevertheless, most studies primarily focus on kinematics in the sagittal plane. Given that clinical patients often exhibit abnormal gait patterns, analyzing movement in the frontal and transverse planes is crucial. Additionally, joint kinetics offer valuable insights into muscle function, making their study equally relevant.

This study aims to compare Theia 3D, a markerless system, to the standard marker-based motion capture system in children with CP, who typically display gait deviations and body deformities to understand whether there are challenges estimating joint kinematics and kinetics.

2. Methods

2.1 Data collection

Fifteen children diagnosed with Cerebral Palsy, 11 males and 4 females, with an average age of 13.66 ± 1.72 years old and different gait patterns were submitted to a clinical gait analysis, captured with standard marker-based and markerless (v2023.1.0.310, Theia Markerless Inc., Kingston, ON, Canada) motion capture systems. The protocol was approved by and executed in accordance with the Faculty of Human Kinetics Ethics Committee (CEFMH-2/2019). An informed consent was previously signed by the parent or the legal guardian of the participant, and the child assent was also obtained after explaining the entire protocol.

Ten equally spaced infra-red Ocqus and Arqus cameras and eight red-green-blue Miqus video cameras (Qualysis AB, Sweden) were used. Each participant was prepared with 36 retroreflective markers placed according to CAST (Calibrated Anatomical Systems Technique) marker set [25].

Both marker-based and markerless systems were connected to Qualisys Track Manager (v2021.03.1 Qualisys AB, Gothenburg, Sweden) to allow simultaneous data acquisition. The frame rate of the recording was 85 Hz for both systems, synchronized in time and space with 3 force plates (9283U014, Kistler Instruments Ltd, Winterthur, Switzerland; FP4060-07&FP4060-05-PT, BERTEC, Columbus OH, USA), sampling at 850Hz.

Participants were instructed to stand in their anatomical position, maintaining a reasonably upright posture. This static trial was used to define the local joint coordinate systems within the marker-based system setup, allowing the construction of the 3D biomechanical model using Visual 3D software (Visual 3D Professional v2021.03.1, Has-Motion, Canada). The static trial was recorded using both systems, and the differences between the pelvic and lower limb joint angles measured with both systems were calculated (marker-based and markerless) for each anatomical plane. After completing the static trial, the anatomical markers were removed from the participants to avoid interference with their natural walking movement.

Participants were then requested to walk on a straight path of approximately 10 meters at self-selected speed, stepping over the force plates. For a trial to be considered for the study, it was required that at least one foot fully contacted with a force plate, which is crucial for a correct calculation of joint moments and powers during the gait cycle. The data acquisition ended once the subject completed 10 successful trials. If necessary, participants were allowed to rest on a chair after each trial.

2.2 Data processing

The PAF (Project Automation Framework) Clinical Gait Module from Qualisys (PAF version 2.0.2.516 Qualisys AB, Sweden) was used in a post-processing way to export the data to C3D files and process the data in Visual 3D software. The following configurations were chosen: 1) The gait events were automatically defined using the force plates (initial contact and toe off for both left and right sides); 2) the computed 3D model consisted in 1 pelvis, 2 thighs, 2 shanks and 2 feet. Lower limb joint angles were calculated using an XYZ Cardan sequence, and ZYX for the pelvis angle relative to the Lab [79]. Joint moments were calculated using Newton-Euler Inverse Dynamics, normalized to subjects' body mass. Marker trajectories were low pass filtered using a Butterworth filter (6Hz), as well as analog signals (25Hz).

For the markerless data, the same PAF Clinical Gait Module from Qualisys was used. In this case, video data were processed with Theia3D, using the default inverse kinematics (IK) 3D pose-estimation, with 6 degrees of freedom (DOF) at the pelvis and 3 DOF at the hip, knee, and ankle joints. To smooth the pose from the IK results, a GCVSPL lowpass filter (8 Hz) was used. The resulting 4x4 pose matrices, for each frame, were exported to C3D format and the results were exported to ASCII file format. The variables were normalized to the gait cycle and 10 gait cycles from each participant were considered for analysis.

The kinematic and kinetic variables were averaged and compared between the systems using the root mean square difference (RMSD). A two-tail paired sample t-test (α=0.05) was conducted using an open-source package for one dimensional statistical parametric mapping (SPM, v0.4.11) on MATLAB (version R2023b, MathWorks, USA).

3. Results

3.1 Kinematics

Table 1. Joint angle differences between marker-based and markerless angular kinematics during the static trial.

Joint	Joint angle difference (º)		
	Sagittal	Frontal	Transversal
Ankle	5.25	1.01	1.75
Knee	1.98	2.71	-5.06
Hip	9.81	1.26	5.13
Pelvis	10.44	0.16	0.37

Differences between the systems were observed during the static trial. In the sagittal plane, the angle measurements at knee joint showed the lowest difference, while the hip and pelvis showed larger inconsistencies (> 9.50º). Differences were minimal in the frontal plane (< 3.0º) and the knee and hip showed considerable differences in the transversal plane.

Table 2. Mean±SD of the RMSD of the kinematic and kinetic variables using both marker-based and markerless systems

	RMSD				
	Kinematics			Moment (Nm/kg)	Power (W/kg)
	Sagittal (º)	Frontal (º)	Transversal (º)		
Ankle	5.95 ± 4.87	5.12 ± 2.77	10.86 ± 7.21	0.20 ± 0.42	0.15 ± 0.11
Knee	4.96 ± 2.40	7.67 ± 7.79	12.19 ± 7.54	0.19 ± 0.39	0.18 ± 0.12
Hip	10.68 ± 5.61	4.65 ± 3.19	16.22 ± 10.45	0.19 ± 0.29	0.20 ± 0.11
Pelvis	11.16 ± 5.25	3.54 ± 1.82	4.47 ± 3.71		

INSERT FIGURE 1 HERE

In the sagittal plane, the markerless and marker-based showed similar waveforms regarding the kinematic joints, however, the markerless system showed underestimated results. The concordance agreement was weak, except for the knee joint, in which the systems recorded almost identical angles for most of the gait cycle. RMSD < 6.0º for the ankle dorsiflexion and knee flexion but > 10.0º for hip flexion and pelvis tilt. Statistically significant differences were observed throughout the gait cycle at the hip flexion ($p < 0.001$) and pelvic tilt ($p < 0.001$), and during the swing phase at the ankle dorsiflexion ($p = 0.002$).

More inconsistencies were observed in other anatomical planes, especially in the transverse plane with a RMSD >10.0º, except for pelvis joint. Nevertheless, during the stance phase, there was a significant difference for pelvic rotation ($p = 0.046$). Also, agreement was lower for the ankle and hip joint rotation angles throughout the stride cycle. Frontal plane RMSDs varied between 3.5º and 8.0º and significant differences were observed at hip adduction ($p = 0.047$) and pelvic obliquity ($p = 0.030$) during early swing cycle.

1.1. Kinetics

INSERT FIGURE 2 HERE

Regarding joint kinetics, statistically significant differences were primarily observed during the swing phase, except for the ankle plantarflexor moment at initial contact ($p = 0.003$) and hip flexor power at loading response phase ($p = 0.017$). The markerless system estimated slightly lower flexor moments than the marker-based system during the stance phase. However, during the swing phase, the average moment values were nearly identical between the systems, particularly at the ankle, despite the statistically significant difference assigned ($p < 0.001$). The ankle joint moment exhibited the largest difference between the systems (RMSD = 0.20 Nm/Kg), while the RMSD of other marker-based joint moments were 0.19 Nm/Kg.

According to the marker-based results, a slight ankle power absorption occurred at initial contact, while the markerless system struggled to measure it. Thereafter, results were similar between the systems throughout the gait cycle. Differences in knee joint power estimations were observed at early stance and terminal swing. The hip joint power demonstrated the most differences between the measurements of the systems during the stance phase (RMSD of 0.20 W/Kg), whereas the ankle joint power had the lowest RMSD (0.15 W/Kg).

2. Discussion

The joint kinematics is highly comparable between marker-based and markerless motion capture systems in the sagittal plane. The knee flexion angle demonstrated very good alignment and agreement between the systems in the static and in the walking trials, being the most comparable joint. Since subjects wore shorts, the skin around their knees was visible, and no markers were placed in that area during the walking trials. This may have made it easier for the markerless system to estimate knee position and orientation.

On the other hand, systematic offsets were observed at the hip and pelvic joint angles in the sagittal plane. Placing markers on the pelvis can be a challenging task due to the complexity of this joint and its large amount of soft tissue, which restricts palpation and the ability to locate bony landmarks. Additionally, clothing can interfere with the markers by covering or moving them. These factors may contribute to the larger discrepancies in the pelvic joint kinematics. Nevertheless, markerless systems also have limitations, as markers can complicate the ability of the algorithm to detect body landmarks.

The waveforms of both systems were similar at the hip and pelvis, however, statistical significance was observed throughout the gait cycle due to a nearly constant offset. After adjusting the offset between the systems, the measurements between the systems would be closely aligned.

Differences in the static trials suggest that these discrepancies seem to arise from the modelling definitions rather than from tracking errors. The offsets in pelvic tilt and hip flexion may be due to the definition of the pelvis neutral position and joint center estimations of the systems. The marker-based system defines the pelvis as more anteriorly tilted and the hip as more flexed than the markerless method does. The discrepancy could result from the fact that different models were used for each system, which allow different DOF. The CAST marker set allows 6 DOF at each segment, while the standard Theia3D lower marker-based model allows 6 DOF at the pelvis and 9 DOF for each leg. This introduces a limitation to the study, however, the CAST markerset provides many benefits for assessing clinical patients, particularly, children with Cerebral Palsy.

Another key limitation of this study is the sample heterogeneity, as participants exhibited different gait patterns, enhancing variability in the joint estimations and statistical testing. SPM considers joint kinematics and kinetics during the entire gait cycle unlike traditional discrete point analysis methods, which only allow to study specific time points. This approach takes into account the joint estimations of each participant and not just the average sample, hence, different gait patterns may reduce the ability to detect significant differences.

The results match closely with findings from similar studies [22][26]. A study on clinical gait patients [24] reported good agreement in ankle and knee kinematics (RMSD < 6.0º) and larger inconsistencies for the hip and pelvis (RMSD > 10.0º) in the sagittal plane. Additionally, the transverse plane showed a greater variability for the lower limb joints, with RMSDs ranging from 9.0º to 19.3º, except for the pelvic rotation (RMSD = 5.2º).

Children with CP typically display lower joint moments and powers when compared to healthy children, represented in grey in Figure 2, since they exhibit a lower walking speed and an impaired muscle function, putting an obstacle in kinetics analysis.

Gait kinetics is determined using inverse dynamics analysis, where inconsistencies due to kinematic and anthropometric data are well documented [27]. These parameters play a crucial role in clinical decision making, making it fundamental for markerless systems to provide accurate measurements in order to be considered viable for clinical use [28]. However, literature fails to address the comparison of marker-based and markerless systems assessing joint kinetics, particularly joint power. This limits the understanding of their reliability and accuracy in clinical applications. Hence, further validation is essential.

Differences in joint moment and power estimation may result from inconsistencies in the segment center of mass (COM) and joint center position estimations between the two systems, which are crucial parameters to perform inverse dynamics calculations. Tang et al. [28] reported differences in the lower limb joint center positions and COM between these two systems and highlighted a 2 cm difference in the hip joint centers, in which the markerless technology defined it posteriorly than the marker-based, potentially affecting the knee joint moment in the same phase. Moreover, joint center estimations between the systems were variable throughout the stride cycle at the ankle and knee joints, although the markerless estimated them more posteriorly at initial contact. The joint moment results (RMSD <= 0.20 Nm/Kg) were consistent with a similar study aimed at the running movement of healthy subjects, which reported that joint moments discrepancies between marker-based and markerless systems were 0.3 Nm/Kg or less.

For this study, the 2023 version of Theia3D was used for the markerless data processing. However, it is not the most updated version anymore and improvements may have been implemented. To conclude, Theia3D kinematics followed similar patterns compared to the marker-based system and seem to be a great tool for assessing the sagittal plane kinematics of children with CP during gait. In the frontal plane acceptable results were determined, but the transverse plane showed much more variability and the worst results between the systems, so the utility of markerless in that anatomical plane remains questionable. The algorithm still requires some improvement in joint center and COM estimation, in order to estimate joint kinetics more accordingly to the marker-based system.

Larger studies involving gait impaired clinical patients should be conducted for stronger findings and statistical analyses. To provide optimal care for CP children, estimation errors must be minimal or inexistent. Despite marker-based systems being the reference method for clinical gait assessment, they are not the gold standard due to inherent limitations, meaning it is unknown whether marker-based systems are more accurate than markerless systems. The utility of the markerless system in assessing children with CP depends on their accuracy of its estimations, emphasizing the need for the biomechanics research community to continue the validation of Theia3D to assess the lower limb joint gait parameters in clinical settings. If validated, Theia3D could offer significant advantages for patients, clinicians and researchers.

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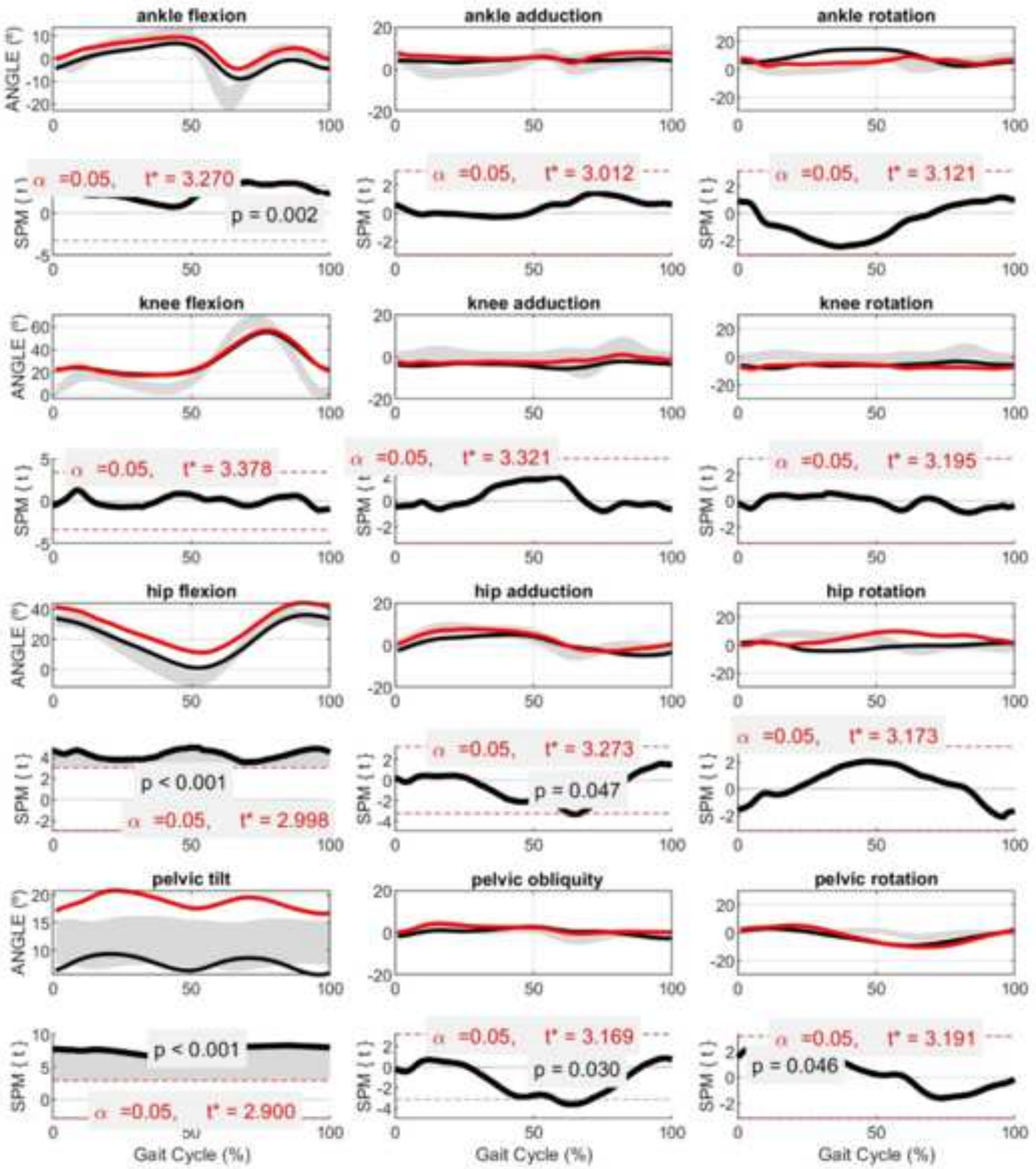
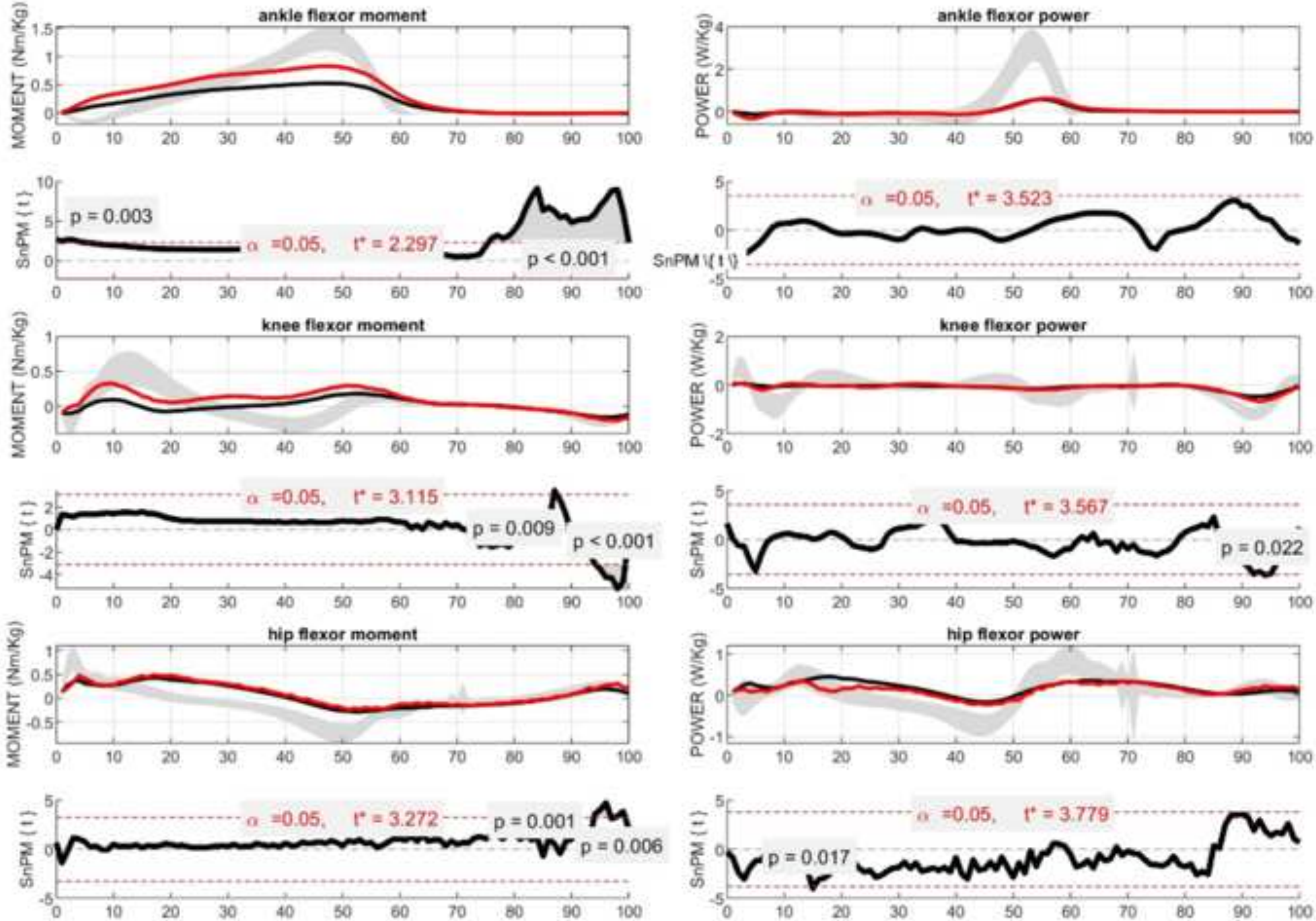
Figure 1



ankle flexion
ANGLE (°)
α =0.05, t* = 3.270
p = 0.002
SPM { t }
ankle adduction
α =0.05, t* = 3.012
ankle rotation
α =0.05, t* = 3.121
knee flexion
α =0.05, t* = 3.378
knee adduction
α =0.05, t* = 3.321
knee rotation
α =0.05, t* = 3.195
hip flexion
p < 0.001
α =0.05, t* = 2.998
hip adduction
α =0.05, t* = 3.273
p = 0.047
hip rotation
α =0.05, t* = 3.173
pelvic tilt
p < 0.001
α =0.05, t* = 2.900
pelvic obliquity
α =0.05, t* = 3.169
p = 0.030
pelvic rotation
α =0.05, t* = 3.191
p = 0.046
Gait Cycle (%)

Figure 2

Click here to access/download;Figure (300 dpi and editable format);Figure 2.tif



CAPTIONS LIST

Figure 1: Comparison of the mean joint kinematics computed with marker-based (red) and markerless (black) motion capture systems. Standard deviation of a healthy population is illustrated (grey).

Figure 2: Comparison of mean joint kinetics of marker-based (red) and Theia markerless (black) systems. Standard deviation of a healthy population is illustrated (grey).

Declaration of interests

☒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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: