Gait & Posture 120 (2025) 217–225

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Full length article

Construct validity of markerless three-dimensional gait biomechanics in healthy older adults

Andreia Carvalho [a,b,c,*], Jos Vanrenterghem [b], Sílvia Cabral [a], Ana M. d'Assunção [a], Filomena Carnide [a], António P. Veloso [a], Vera Moniz-Pereira [a]

[a] LBMF, CIPER, Faculdade de Motricidade Humana, Universidade Lisboa, Lisboa P-1499-002, Portugal
[b] Musculoskeletal Rehabilitation Research Group, Faculty of Movement and Rehabilitation Sciences, Leuven KU, Belgium
[c] Escola Superior de Tecnologias da Saúde de Lisboa, Instituto Politécnico de Lisboa, Lisboa 1990-096, Portugal

ARTICLE INFO

Keywords:
Methods comparison
Walking
Kinematics
Kinetics
Marker-based
Correlation

ABSTRACT

Background and aim: Gait changes due to aging can result in functional limitations and a higher risk of falls, with older adults showing alterations in joint angles and moments. Marker-based gait analysis is not widely used in clinical settings due to its complexity and discomfort, especially in older adults. Recent advances in markerless motion capture, such as Theia3D, offer a promising alternative. This study aims to assess the construct validity of a markerless motion capture system for gait analysis in healthy older adults.
Methods: A cross-sectional study included 30 healthy community-dwelling older adults. Gait data was collected using marker-based and markerless motion capture systems in randomized order, with participants wearing tight-fitting minimal clothes plus 46 reflective markers attached, or their usual clothes, respectively. Joint kinematics (including range of motion) and kinetics were analyzed, and correlations between methods (Rxy) were assessed. Bland&Altman analysis was used to measure agreement. Root-mean-square differences (RMSD) were computed. Acceptable thresholds were set at $\leq 5^{\circ}$ for kinematic and at $\leq 10\,\%$ of signal amplitude for kinetics.
Results: Strong correlations (Rxy$\geq$0.7) were found between the systems for sagittal plane kinematics (except for the pelvis), particularly for knee and ankle joints. A low agreement was detected in sagittal plane hip and pelvis kinematics, along with RMSD exceeding 5º. Weaker correlations and poor agreement were observed for transverse and frontal plane motions. Overall strong correlations were found for kinetics, except for the joint ankle inversion-eversion moment, and poor agreement for the frontal and transverse planes.
Conclusion: Overall markerless motion capture demonstrated good construct validity for measuring sagittal plane gait lower-limb gait kinematics (excluding pelvis) and kinetics in healthy older. However, considering the agreement between methods and the results for the other movement planes, further validation is required before markerless and marker-based systems can be used interchangeably in gait assessments.

1. Introduction

Gait changes associated with aging may contribute to functional limitations in the older population [1]. Literature suggests that age affects gait mechanics, with older adults exhibiting reduced pelvic rotation, reduced hip and ankle joint movements in the sagittal plane, and reduced internal peak plantarflexion ankle moments [1,2]. These gait changes have been linked to critical health concerns, such as an increased risk of falls [3,4]. However, given the necessity for a laboratory environment and associated time-consuming data collection and processing, current gait analysis methods are unlikely to be widely implemented in clinical settings [5]. Motion capture typically involves placing markers on the skin, which can be challenging in some populations, like older adults [6], often resulting in discomfort that may interfere with their gait patterns [7]. This has created a demand for accurate motion capture methods that are less time-consuming and

* Correspondence to: Laboratório de Biomecânica e Morfologia Funcional, Faculdade de Motricidade Humana, Estrada da Costa, Cruz Quebrada-Dafundo 1499-002, Portugal
E-mail addresses: andreiafjcarvalho@gmail.com (A. Carvalho), jos.vanrenterghem@kuleuven.be (J. Vanrenterghem), scabral@fmh.ulisboa.pt (S. Cabral), aassuncao@edu.ulisboa.pt (A. M. d'Assunção), fcarnide@fmh.ulisboa.pt (F. Carnide), apveloso@fmh.ulisboa.pt (A.P. Veloso), veramps@fmh.ulisboa.pt (V. Moniz-Pereira).

https://doi.org/10.1016/j.gaitpost.2025.04.022
Received 13 November 2024; Received in revised form 12 March 2025; Accepted 21 April 2025
Available online 25 April 2025

feasible within real-world environments [8,9]. Consequently, interest in markerless multi-camera motion capture has grown, driving research on its validation [10,11].

Recent studies have compared marker-based methods with a novel commercially available markerless motion capture system, Theia3D (Theia Markerless Inc., Kingston, Ontario, Canada), which utilizes deep-learning anatomical landmark prediction from video data [12–16]. Some of these studies assessed gait in young adults reporting root-mean-square differences (RMSD) $\leq 8^{\circ}$ in the lower-limb joint angles, and RMSD $\leq 2.5\,\%$ height×weight for lower-limb moments [12, 14]. One study focused on an abnormal gait pediatric population and showed preliminary promising results (RMSD <6º) [15]. The authors strongly recommended further validation studies involving specific populations. Particularly validation in older adults is still lacking. As markerless pose estimation relies on neural networks training, variations in sample anthropometric characteristics may affect its outcome [12].

A consistent feature of those studies investigating the validity of gait mechanics through markerless motion capture is the simultaneous collection of measurements from participants wearing minimal clothing and markers. Since the markerless system is robust to clothing [13, 17–19], this methodological option facilitates data collection from the same movement trials. However, one of the significant advantages of markerless systems is the ability to assess participants in their usual attire without markers placed on the skin, making validation studies under these conditions meaningful. Therefore, this study aims to assess the construct validity of the markerless motion capture method for measuring three-dimensional (3D) gait mechanics in a sample of healthy older adults, wearing their usual attire. Based on previous studies [13, 14] we hypothesized that gait kinematics and kinetics time-profiles obtained from the markerless system are similar to those obtained with the marker-based system. We also expected less agreement between methods regarding hip and pelvis angles and the transverse plane kinematics, and concerning the ankle frontal plane moments.

2. Methods

2.1. Study design and participants

A cross-sectional study was conducted. The sample size was determined based on the construct convergent validity testing (correlations between methods). A minimum of 29 participants was necessary for a two-tailed test, 5 % level of significance, 80 % power, and an effect size of 0.5, as strong-to-moderate correlations were expected, based on previous studies [12,14,15]. Thus, a convenience sample of 30 older adults was recruited from Lisbon Living+ and researchers' networks. Community-dwelling healthy adults aged ≥ 65, who walk independently without a walking aid, were considered eligible. Subjects diagnosed with clinical conditions/taking medications affecting walking ability, experiencing lower-limb pain/symptoms, with cognitive impairment [Montreal Cognitive Assessment (MoCA) score < 23], and/or obesity (BMI $>30 Kg/m^2$) were excluded. Participants provided written informed consent, and the study protocol received approval (Faculty Ethics Committee: CEIFMH No.1/2022).

2.2. Data collection procedure and experimental setup

Data was collected in a single laboratory session. To verify the inclusion/exclusion criteria and to characterize the sample, the participant's socio-demographic-health information was gathered and the MoCA [20] was conducted. Subsequently, participants completed the Composite Physical Function Scale (CPF) [21], a self-report tool assessing functional ability. Body mass and height were measured. Markerless and marker-based gait data collection were performed separately, in random order (Qualisys Track Manager, Qualisys AB, Gothenburg, Sweden), each recording at 85 Hz [22] synchronized in time and space with three floor-embedded force plates (9283U014, Kistler Instruments Ltd, Winterthur, Switzerland; FP4060–07 & FP4060–05-PT, BERTEC, Columbus OH, USA), sampling at 850 Hz. Marker-based data was collected with 9 infrared cameras (Oqus, Qualisys AB). Participants wore shoes and tight-fitting minimal clothes to allow the placement of 46 reflective markers on the participants' trunk and lower-limbs by one experienced physiotherapist, following a marker-setup based on the calibrated anatomical system technique [23] (Fig. 1, left/middle panels). Markerless data was collected using 8 Miqus video cameras (Qualisys AB), with participants wearing their usual clothes and the same shoes (Fig. 1, right panel). After a familiarization trial, participants walked along the laboratory diagonal (12 m), at their normal comfortable speed over periods of 1–2 minutes. A standing static trial was recorded in the marker-based measurements.

Additionally, during marker-based data collection, markerless data was recorded simultaneously, allowing assessment of clothing's impact on markerless data (supplementary material 1).

2.3. Data processing

Theia3D [v2023.1.0.310(patch: 1)-TMBatch] was used to process video data through the default Inverse Kinematics (IK) 3D pose estimation [3 degrees of freedom (DOF) at the hip, knee, and ankle joints and 6 DOF for the pelvis and thorax], filtered with a GVCSPL (Woltring generalized cross-validity quintic-spline) at a cut-off frequency of 8 Hz, determined by residual analysis. Next, the 4×4 pose matrices were exported from Theia3D to c3d format.

For the marker-based data, an 8-segment model (thorax, pelvis, thighs, shanks, and feet) was built and the same IK approach was used, with IK filter set at 8 Hz (details available in supplementary material 2).

In both cases, inertial parameters were determined according to Dempster's [24] and Hanavan's approach [25].

A 4th-order Butterworth filter (8 Hz) was applied to analog signals. Stride events were detected using ground reaction force data (20 N threshold). Lower-limb joint angles were calculated using an XYZ Cardan sequence, and ZYX for the pelvis segment angles [26], whereas internal joint moments were computed using Newton-Euler inverse dynamics, normalized to the participants' body mass, and expressed relative to the proximal segment. The marker-based modeling and all variable computations were performed in Visual3D (HAS-Motion, Inc, Canada).

Eight time-normalized right gait cycles were randomly selected [27] and averaged from each system, per participant, considering that systematic inter-limb differences are unexpected in healthy participants [28].

2.4. Data analysis

The cross-correlation coefficient (Rxy) [29] was calculated to measure the similarity between markerless and marker-based joint angle and joint moment curves for each participant and averaged. The Pearson correlation coefficient (r) was also computed for lower-limb range of motion (ROM) and peak ankle plantar flexion moment, given the importance of these parameters in older adults (particularly on the sagittal plane) [1]. A coefficient above 0.69 was considered a strong correlation (very strong above 0.89), moderate between 0.40 and 0.69, and weak below 0.40. Correlations between 0.0 and 0.10 were deemed negligible [30].

Fig. 1. Posterior (left) and anterior (middle) views of marker placement, and their labeling. Example of clothing worn for the markerless data collected (right). Abbreviations: R_: right; L_: left; SAE: acromioclavicular joint; SJN: suprasternal notch; SXS: xiphisternal joint; TV: thoracic vertebrae; CRI: iliac crest; IPS/IAS: posterior/anterior spines; FTC: greater trochanter; TH1–4: thigh cluster (4 markers); FLE/FME: femoral epicondyles; SK1–4: shank cluster (4 markers); FAL/TAM: malleolus; FC: foot cluster (1 marker); FM: metatarsal heads; FCC: calcaneus.

The agreement between the two methods was also assessed, as correlations do not inform how close the measurements are [31], facilitating translation into clinical relevance. Thus, the mean difference (bias) between methods ($\overline{X}_{diff}$) (obtained by subtracting the markerless from the marker-based data) and 95 % Limits of Agreement (LoA) (95 % LOA=$\overline{X}_{diff}\pm1.96$ *SD_{diff}, where SD_{diff} are the standard deviation of the difference), based on Bland&Altman analysis [32] were computed for the ROM (defined as maximum-minimum joint angles) of the pelvis, hip, knee, and ankle in the 3 movement planes, and peak ankle plantarflexion moment, after checking for the relationship between the differences and the mean. When this assumption was violated, logarithmic transformation was considered and tested (supplementary material 3). Given the interpretation of the results does not seem to change and that its comparison with the remaining parameters would be complex, even back-transforming the results, we decided to keep the presentation of the original data.

A similar approach was also performed for the 3D lower-limb joint angles and moments for the time-series data, based on Røislien et al. [33]. Additionally, the RMSD was computed. Although there are no previously published reference thresholds for the differences in joint angles and ROM, bias and RMSD of ≤ 5º were considered acceptable (and bias±5º for LoA) [34]. For joint moments, differences ≤ 10 % of the signal amplitude (and bias $\pm$ 10 % for LoA) were defined as an arbitrary threshold to facilitate interpretation.

The gait speed obtained using both methods was compared using a paired *t*-test. Computations were performed using Microsoft Excel ($\alpha<0.05$) and plots built in Python 3.11.7.

3. Results

This study included 30 participants (16 males and 14 females; 75.0 $\pm$ 7.6 years old; Body Mass Index 25.0 $\pm$ 2.5 kg/m^2). The MoCA score was 25.7 $\pm$ 1.9, and the CPF Scale was 23.7 $\pm$ 0.9 points, representing advanced physical function. The mean walking speed of marker-based and markerless measurements was not significantly different (1.24 $\pm$ 0.15 vs 1.27 $\pm$ 0.15 m/s, t(30) = 2.039, $p = 0.506$).

A very strong correlation (Rxy≥0.9) between marker-based and markerless methods was found for the sagittal plane lower-limb kinematics curves, except for the pelvis, which revealed a weak correlation (Rxy= 0.17) (Fig. 2a/c/e/g). Hip flexion/extension and anterior/posterior pelvis tilt angles displayed bias of more than 5º across ≈ 50 % of the gait cycle, as well as knee frontal plane angles in middle swing (Fig. 2b/d/f/h). Overall, correlation in the frontal and transverse planes ranged from weak to moderate (0.17–49), except for the pelvis frontal plane (negligible), pelvis transverse plane, and ankle frontal plane (strong). The functional LoA for transverse plane hip, knee, and ankle motion all exceeded the threshold of 5º during the entire gait cycle (Fig. 2b/d/f/h). The lowest RMSD value was found for the ankle plantar/dorsal flexion (2.9º) and the highest RMSD were found for hip flexion/extension (7.8º) and knee and ankle internal/external rotation (7.7º and 7.5º, respectively). The variability associated with the marker-based system (evidenced by standard deviation) was globally higher than that of the markerless system, especially in the frontal and transverse planes (Fig. 2a/c/e/g).

Strong correlation between methods was found for knee and ankle on the sagittal plane ROM (r = 0.70 and 0.76, respectively), and a

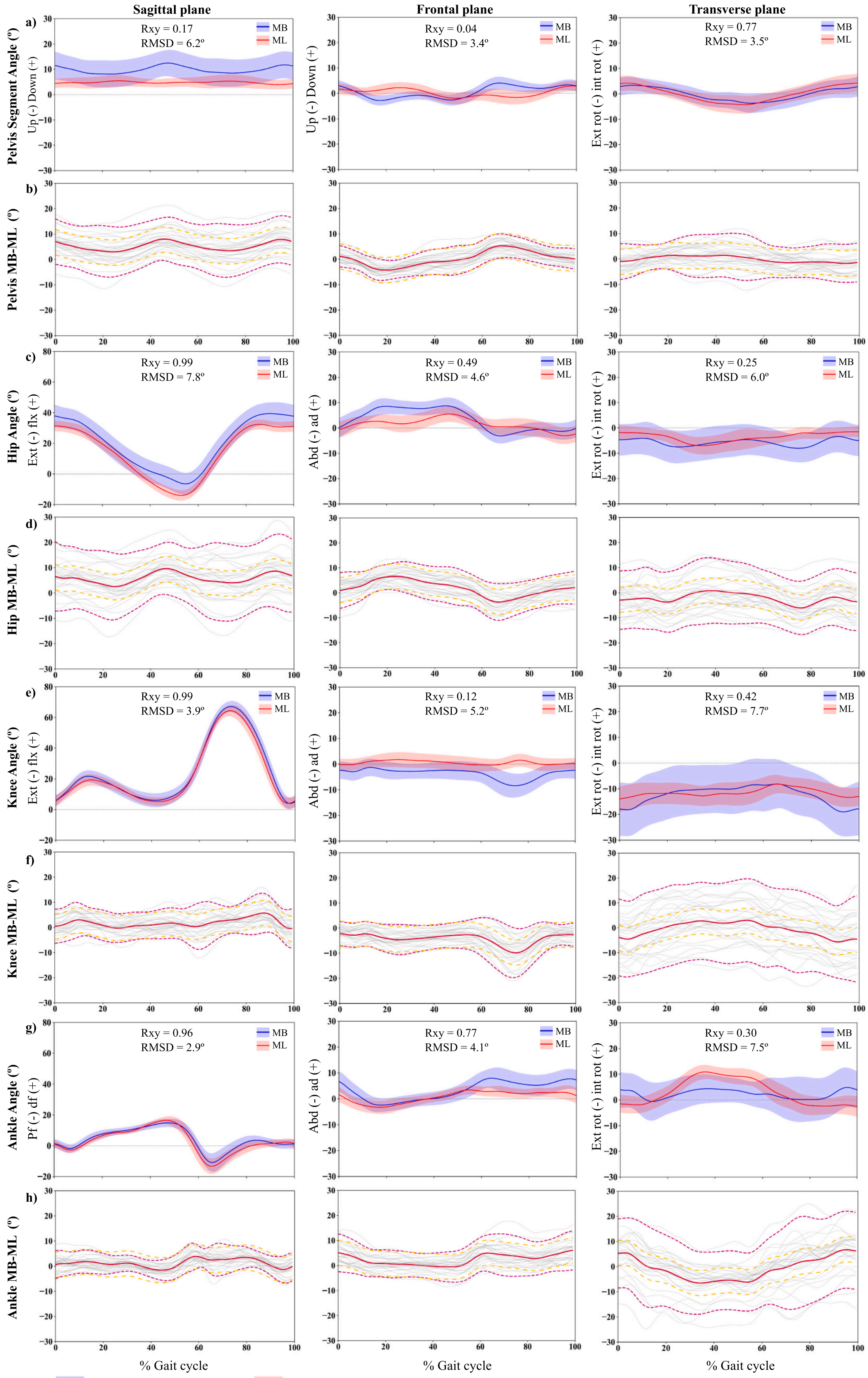

Fig. 2. Kinematics plots. Averaged gait cycle waveforms (a, c, e, g) and mean and individual difference waveforms (bias, red line), with functional limits of agreement (LoA, pink dashed lines) (b, d, f, h), comparing marker-based and markerless lower-limb joint angles. Yellow dashed lines correspond to the arbitrary threshold.

Table 1
Correlation coefficients (r) and p-values for lower-limb range of motion (ROM) values from marker-based and markerless observations (*correlation is significant at the 0.05 level).

ROM		Correlation Coefficient (r)	*p-value*
Pelvis	**Sagittal**	0.31	0.098
	Frontal	0.01	0.947
	Transverse	0.18	0.352
Hip	**Sagittal**	**0.60** *	0.001
	Frontal	0.35	0.062
	Transverse	0.004	0.984
Knee	**Sagittal**	**0.70** *	< 0.001
	Frontal	0.18	0.341
	Transverse	0.12	0.516
Ankle	**Sagittal**	**0.76** *	< 0.001
	Frontal	−0.08	0.663
	Transverse	0.32	0.089

moderate correlation for hip flexion/extension ROM ($r = 0.60$). Remaining correlation coefficients were not significant (Table 1). Bias between ROM measurements was below 5°, except for the knee and ankle in the transverse plane (6.4° and 5.1°, respectively). All LoA ranges were higher than 5°, except for the pelvis sagittal plane motion. Ankle transverse plane, pelvic rotation, and hip adduction/abduction ROMs showed the largest LoA ranges (20.6°, 22.1°, and 21.7°, respectively) (Fig. 3). Marker-based ROM values were generally higher than markerless ROM values, except for the hip and ankle sagittal plane, and the pelvis and ankle transverse plane.

Lower-limb joint moment curves showed very strong correlations between methods, except for hip internal/external rotation moments (Rxy=0.80) and ankle frontal plane moments (Rxy=0.56) (Fig. 4a/c/e).

Poor agreement between methods was detected for the ankle and knee adduction/abduction as well as hip internal/external rotation moments, showing wider LoA, particularly during the stance phase. Hip flexion/extension moments showed large variations in differences

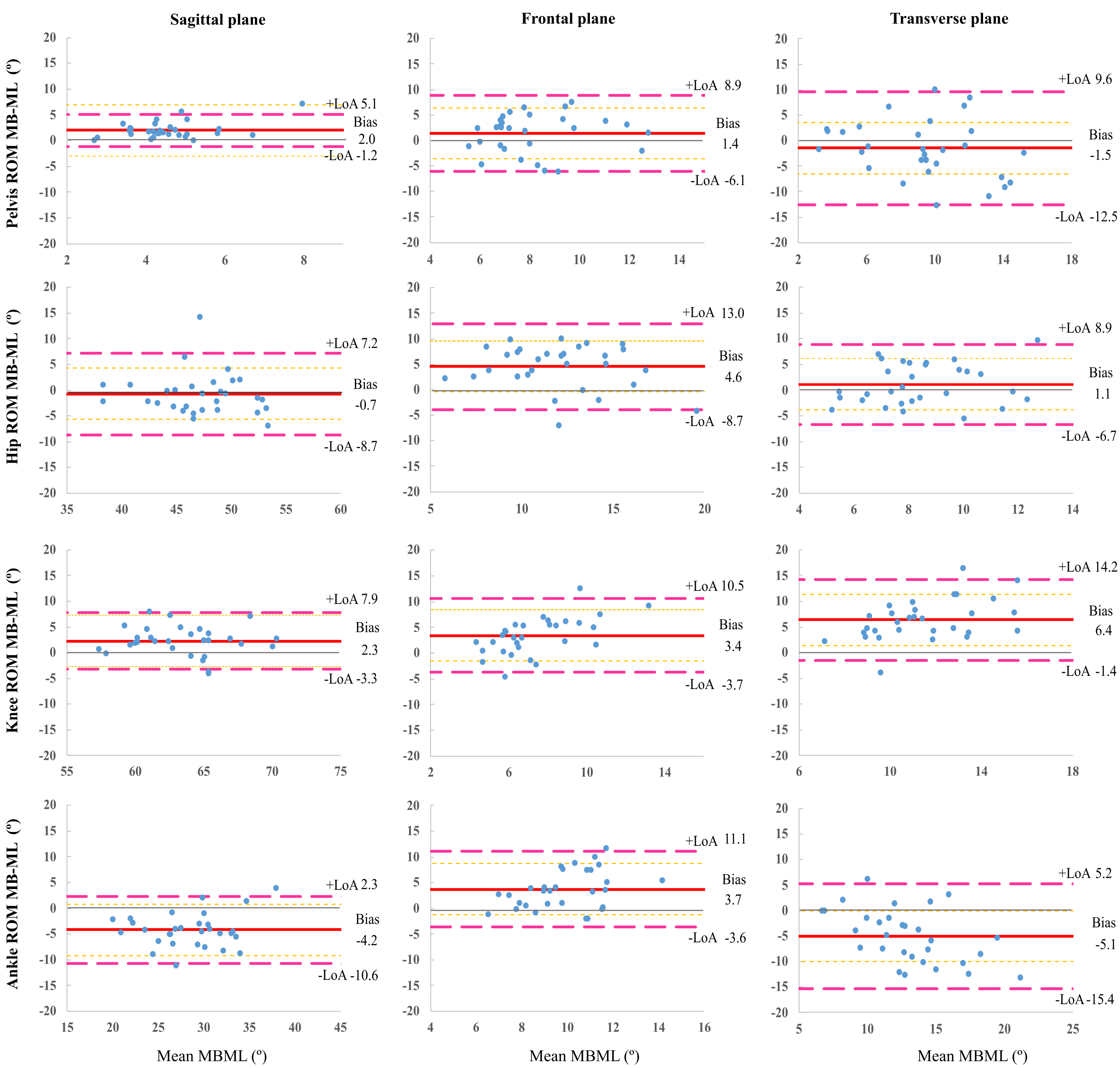

Fig. 3. Bland-Altman plots. Bland-Altman comparisons between marker-based and markerless lower-limb range of motion (ROM) values with 95 % limits of agreement (pink dashed lines). Yellow lines correspond to the arbitrary threshold.

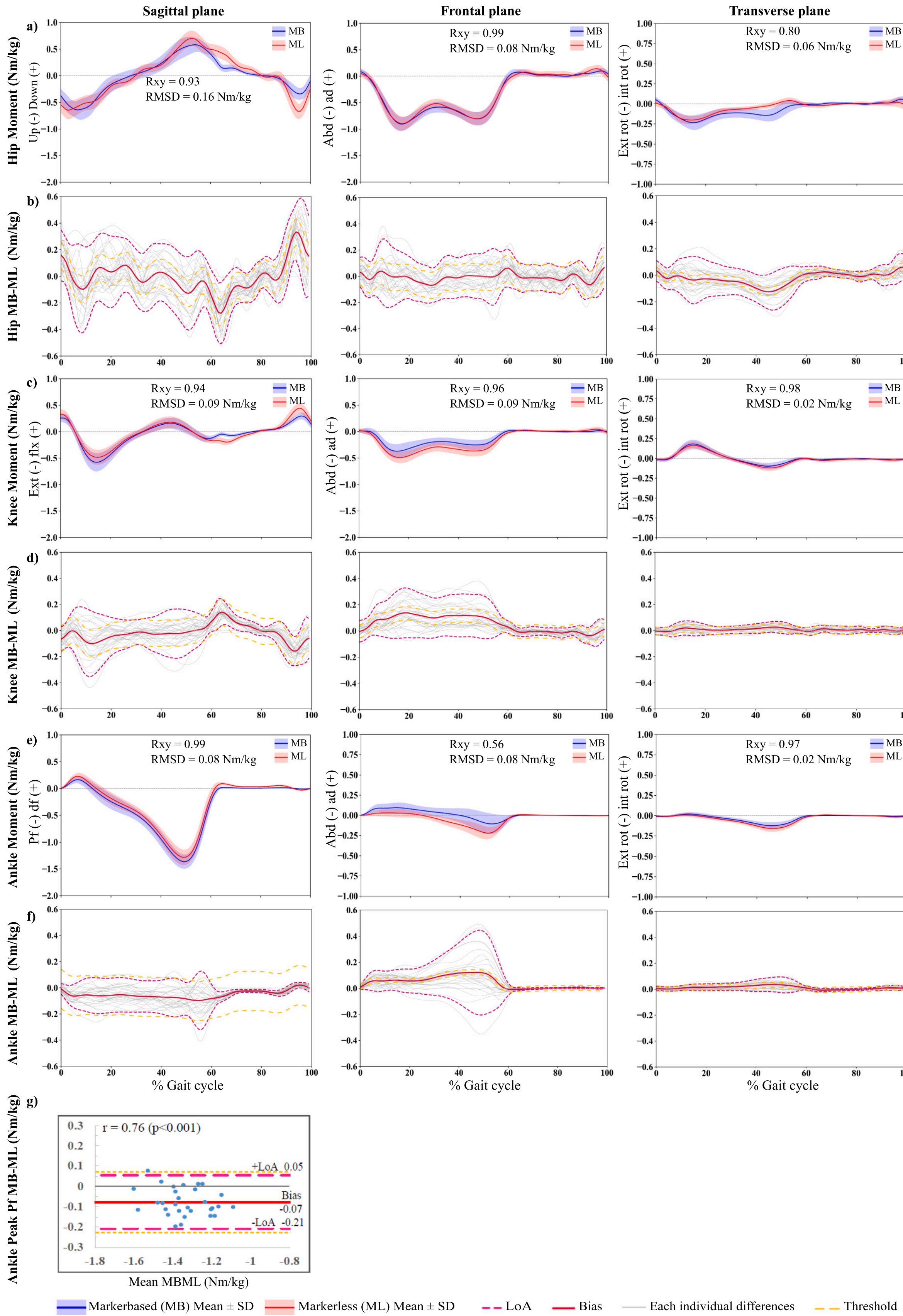

Fig. 4. Kinetics plots. Averaged gait cycle waveforms (a, c, e) and mean and individual difference waveforms (bias, red line), with functional limits of agreement (LoA, pink dashed lines) (b, d, f), comparing marker-based and markerless lower-limb joint moments; Bland–Altman comparison with 95 % limits of agreement (pink dashed lines) for the ankle peak plantarflexion moment (g). Yellow dashed lines correspond to the arbitrary threshold.

between methods across the gait cycle. Still, for most kinetic parameters the bias but not the LoA was lower than 10 % of signal magnitude. The RMSD ranged between 0.02 and 0.16 Nm/Kg, with the highest value for the hip flexion/extension joint moment. A strong correlation was found between methods for peak ankle plantarflexion moment. Its bias and LoA were within the defined threshold (0.15 Nm/Kg) (Fig. 4g).

4. Discussion

This study aimed to assess the construct validity of a markerless motion capture system for gait analysis in healthy older adults. Overall, sagittal plane gait kinematics and kinetics curves obtained from a markerless system are strongly correlated with those acquired with a marker-based system, showing high agreement for ankle and knee joint curves on this plane. Poorer agreement was found for sagittal plane pelvis and hip angles. Weaker correlations and poorer agreement were observed in transverse and frontal plane kinematics. For ROM values, the strongest correlation was detected for the ankle in the sagittal plane, albeit with a higher bias than the other joints for this plane. In general, the LoA exceeded the defined thresholds. Furthermore, weaker correlations and less agreement between methods in ankle frontal plane moments were observed, supporting our hypothesis.

The absence of a gold standard method in this study limits the interpretation of our results. Therefore, more than providing a definitive answer about which method is better to assess movement in the older population, this study aimed to provide knowledge on the comparison between the most commonly used non-invasive method and the new markerless approach, i.e. to test if the markerless system has construct validity when compared to the marker-based system.

The very strong correlations between marker-based and markerless sagittal plane kinematics, except for the pelvis, and weaker correlations for the other movement planes (mainly the transverse plane) are consistent with Song et al. [14] and Kanko et al. [12]. The greater sagittal plane range of motion in most of the lower-limb joints during gait possibly makes it easier for motion capture systems to track the pose.

Whilst correlations between pelvic segment angles were not assessed in the aforementioned study [14], a strong correlation and larger differences between hip sagittal plane motion were also detected in that study. These authors related their findings to the pelvis segment definitions, as the marker-based model considers an individual's natural pelvic tilt. However, in our case, this reasoning does not seem to fully justify the larger biases found for both the hip and pelvis in the sagittal plane, which varied throughout the gait cycle. If differences were due solely to the reference frame definition, a constant difference would be expected throughout the cycle. Further, although the bias for hip and pelvis ROM in this plane is approximately zero, the wide LoA (mainly at the hip) suggests variability in the differences between both systems in these parameters. Considering these results, we hypothesize that the low range of motion in the pelvis in this plane, compared to the movement at the hip, along with different model definitions, may also explain the weak correlations in the pelvis, and the overall differences for the hip and the pelvis angles. A recent study focused on clinical and healthy individuals reported weak correlations and RMSD exceeding 5º for pelvic motion in the sagittal plane [35]. Challenges in pelvis pose tracking have been documented in studies using both methods [13,36]. However, there appears to be a consistent tendency for underestimating pelvic anterior tilt across different markerless systems [37]. Regarding our study, the increase in trunk and upper body fat with aging, along with overall adiposity, may be adding to this difficulty.

Furthermore, a cross-talk effect appears to occur in both systems in the mid-swing phase of the frontal plane knee joint motion. This phenomenon is well-documented in marker-based systems, often attributed to errors in anatomical landmark palpation [38]. It seems that the markerless system is also influenced by this effect, which was already observed in the study by Wren et al. [15].

The lower-limb joint moment curves showed a very strong correlation between methods for all three joints, except for the hip transverse and the ankle frontal planes. These higher correlations compared to the kinematics, follow the results of Song et al. [14]. The highest difference between methods for frontal plane ankle moments was previously reported in a study assessing treadmill running [13]. However, this difference was less clear in our study.

The higher peak hip flexion moment and lower knee extension moment obtained from the markerless system are also consistent with results of previous studies [13,39]. Conversely, compared to the aforementioned studies, the plantarflexion peak moment estimated by the marker-based system in our data was higher, similar to the results of Song et al. [14].

Concerning the RMSD between systems, the values for the ankle and knee joint angle in the sagittal plane differ only slightly from the differences reported in a test-retest study in an older population using Theia3D [27]. Furthermore, the RMSD for knee internal/external rotation moment is the same (0.02 Nm/kg), suggesting that the difference identified between the marker-based and markerless systems overlaps with the differences between the two sessions with the markerless system.

Another important finding was that the variability of marker-based signals was globally higher than that of markerless signals, especially for the frontal and transverse planes, which seems to be aligned with previous findings [12,13]. Compared to bi-planar videoradiography, arguably the gold standard method for joint angular motion, the variability of marker-based seems to be similar [40]. The fact that markerless motion has a lower variability, may infer a central tendency effect embedded within the anatomical marker detection algorithms. However, this hypothesis appears not to be confirmed by Bousigues et al. [41] in which the effect of the markerless inconsistencies was reported to be at least as large as the effect of marker-based soft tissue artifact. As such, this warrants further investigation which is not covered by our study.

Some methodological considerations of our study should be noted. The use of asynchronous trials may be perceived as a limitation. However, a major benefit of markerless motion capture systems is that subjects can wear their usual attire and do not need markers placed. Indeed, our analysis available in supplementary material 1 showed that differences between markerless minimal-versus-usual clothing and the markerless inter-session usual clothing data are small. Thus, it is therefore worth identifying the difference between the two systems, applied in the way they are used in practical contexts. Another important fact in this type of study is that new versions of the markerless system, implementing updated algorithms, are regularly being released and can have some impact on the measurements [42], so the detailed aspects of our results are only valid for the version used in this study.

In conclusion, markerless motion capture demonstrated good overall construct validity for measuring sagittal plane lower-limb gait kinematics (excluding the pelvis) and kinetics, in healthy older adults. Conversely, frontal and transverse plane kinematics showed weak to moderate correlation with marker-based data. The sagittal plane knee and ankle joint angles showed the smallest differences between systems. Given the good agreements for signals such as sagittal plane ankle movement, and the peak ankle plantarflexion moments, the markerless system is a promising tool for performing gait analysis in older adults. However, based on the observed correlations and biases in certain parameters, for the time being, we would advise that both systems should not be used interchangeably for 3D gait analysis of the lower limbs.

CRediT authorship contribution statement

Carvalho Andreia: Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Vanrenterghem Jos**: Writing – review & editing, Supervision, Methodology, Conceptualization. **Cabral Sílvia**: Writing – review &

editing, Methodology, Investigation. **Assunção Ana**: Writing – review & editing, Investigation. **Carnide Filomena**: Writing – review & editing, Investigation. **P. Veloso António**: Writing – review & editing, Resources, Funding acquisition. **Moniz-Pereira Vera**: Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors have no conflicts of interest to declare.

Acknowledgments

The authors are grateful to all the subjects who volunteered to participate in this study. This work was supported by Fundação para a Ciência e a Tecnologia: Grant numbers DOI 10.54499/2020.07958.BD (PhD Grant), DOI: 10.54499/UIDB/00447/2020, and DOI: 10.54499/UIDP/00447/2020) attributed to CIPER–Centro Interdisciplinar de Estudo da Performance Humana (unit 447).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gaitpost.2025.04.022.

References

[1] K.A. Boyer, R.T. Johnson, J.J. Banks, C. Jewell, J.F. Hafer, Systematic review and meta-analysis of gait mechanics in young and older adults, Exp. Gerontol. 95 (2017) 63–70, https://doi.org/10.1016/j.exger.2017.05.005.

[2] A.C. Cury, R.Z. Pinto, F.O. Madaleno, R.A. Resende, Do older adults present altered pelvic and trunk movement pattern during gait? A systematic review with meta-analysis and GRADE recommendations, Braz. J. Phys. Ther. 25 (2021) 484–499, https://doi.org/10.1016/j.bjpt.2021.01.003.

[3] D.C. Kerrigan, L.W. Lee, J.J. Collins, P.O. Riley, L.A. Lipsitz, Reduced hip extension during walking: healthy elderly and fallers versus young adults, Arch. Phys. Med. Rehabil. 82 (2001) 26–30, https://doi.org/10.1053/apmr.2001.18584.

[4] Y. Kobayashi, H. Hobara, S. Matsushita, M. Mochimaru, Key joint kinematic characteristics of the gait of fallers identified by principal component analysis, J. Biomech. 47 (2014) 2424–2429, https://doi.org/10.1016/j.jbiomech.2014.04.011.

[5] C. Buckley, L. Alcock, R. McArdle, R.Z.Ur Rehman, S. Del Din, C. Mazzà, A. J. Yarnall, L. Rochester, The role of movement analysis in diagnosing and monitoring neurodegenerative conditions: insights from gait and postural control, Brain Sci. 9 (2019) 1–21, https://doi.org/10.3390/brainsci9020034.

[6] V. Moniz-Pereira, S. Cabral, F. Carnide, A.P. Veloso, Sensitivity of joint kinematics and kinetics to different pose estimation algorithms and joint constraints in the elderly, J. Appl. Biomech. 30 (2014) 446–460, https://doi.org/10.1123/jab.2013-0105.

[7] M. Sandau, H. Koblauch, T.B. Moeslund, H. Aanæs, T. Alkjær, E.B. Simonsen, Markerless motion capture can provide reliable 3D gait kinematics in the sagittal and frontal plane, Med. Eng. Phys. 36 (2014) 1168–1175, https://doi.org/10.1016/j.medengphy.2014.07.007.

[8] L. Wade, L. Needham, P. McGuigan, J. Bilzon, Applications and limitations of current markerless motion capture methods for clinical gait biomechanics, PeerJ 10 (2022) 1–27, https://doi.org/10.7717/peerj.12995.

[9] G.A. Lichtwark, R.W. Schuster, L.A. Kelly, S.G. Trost, A. Bialkowski, Markerless motion capture provides accurate predictions of ground reaction forces across a range of movement tasks, J. Biomech. 166 (2024), https://doi.org/10.1016/j.jbiomech.2024.112051.

[10] S. Harsted, A. Holsgaard-Larsen, L. Hestbæk, E. Boyle, H.H. Lauridsen, Concurrent validity of lower extremity kinematics and jump characteristics captured in pre-school children by a markerless 3D motion capture system, Chiropr. Man. Ther. 27 (2019) 1–16, https://doi.org/10.1186/s12998-019-0261-z.

[11] L. Needham, M. Evans, D.P. Cosker, L. Wade, P.M. McGuigan, J.L. Bilzon, S. L. Colyer, The accuracy of several pose estimation methods for 3D joint centre localisation, Sci. Rep. 11 (2021) 1–11, https://doi.org/10.1038/s41598-021-00212-x.

[12] R.M. Kanko, E.K. Laende, E.M. Davis, W.S. Selbie, K.J. Deluzio, Concurrent assessment of gait kinematics using marker-based and markerless motion capture, J. Biomech. 127 (2021) 110665, https://doi.org/10.1016/j.jbiomech.2021.110665.

[13] R.M. Kanko, J.B. Outerleys, E.K. Laende, W.S. Selbie, K.J. Deluzio, Comparison of concurrent and asynchronous running kinematics and kinetics from marker-based and markerless motion capture under two clothing conditions, J. Appl. Biomech. 40 (2024) 129–137, https://doi.org/10.1123/jab.2023-0069.

[14] K. Song, T.J. Hullfish, R. Scattone Silva, K.G. Silbernagel, J.R. Baxter, Markerless motion capture estimates of lower extremity kinematics and kinetics are comparable to marker-based across 8 movements, J. Biomech. 157 (2023), https://doi.org/10.1016/j.jbiomech.2023.111751.

[15] T.A.L. Wren, P. Isakov, S.A. Rethlefsen, Comparison of kinematics between Theia markerless and conventional marker-based gait analysis in clinical patients, Gait Posture 104 (2023) 9–14, https://doi.org/10.1016/j.gaitpost.2023.05.029.

[16] A. Chaumeil, B.K. Lahkar, R. Dumas, A. Muller, T. Robert, Agreement between a markerless and a marker-based motion capture systems for balance related quantities, J. Biomech. (2024), https://doi.org/10.1016/j.jbiomech.2024.112018.

[17] V.T. Keller, J.B. Outerleys, R.M. Kanko, E.K. Laende, K.J. Deluzio, Clothing condition does not affect meaningful clinical interpretation in markerless motion capture, J. Biomech. 141 (2022) 111182, https://doi.org/10.1016/j.jbiomech.2022.111182.

[18] B. Horsak, H. Kainz, B. Dumphart, Repeatability and minimal detectable change including clothing effects for smartphone-based 3D markerless motion capture, J. Biomech. 175 (2024) 112281, https://doi.org/10.1016/j.jbiomech.2024.112281.

[19] S. Augustine, R. Foster, G. Barton, M.J. Lake, R. Sharir, M.A. Robinson, The inter-trial and inter-session reliability of Theia3D-derived markerless gait analysis in tight versus loose clothing, PeerJ 13 (2025) 1–15, https://doi.org/10.7717/peerj.18613.

[20] S. Freitas, M.R. Simões, L. Alves, I. Santana, Montreal cognitive assessment (MoCA): normative study for the Portuguese population, J. Clin. Exp. Neuropsychol. 33 (2011) 989–996, https://doi.org/10.1080/13803395.2011.589374.

[21] V. Moniz-Pereira, T.F. Silva, E.B. Cruz, F. Carnide, The European Portuguese version of the composite physical function scale: cross-cultural adaptation and validation in community-dwelling older adults, J. Aging Phys. Act. 31 (2023) 860–865, https://doi.org/10.1123/japa.2022-0135.

[22] R.M. Bartlett, C.J. Payton, C.E. Milner, A. Lees, M. Lake, A. Burden, V. Baltzopoulos, J. Challis, D. Mullineaux, M. Yeadon, M. King, Biomechanical Evaluation of Movement in Sport and Exercise - The British Association of Sport and Exercise Sciences Guidelines, Routledge, New York, 2008, https://doi.org/10.4324/9780203095546-5.

[23] A. Cappozzo, F. Catan, U. Della Crocel, A. Leardini, Position an ' d orientation in space of bones during movement: anatomical frame definition and determination, 10 (1995) 171–178.

[24] W. Dempster, Space requirements of the seated operator geometrical, kinematic, and mechanical aspects of the body, with special reference to the limbs Technical Report (55-159) (AD 87892), Ohio, 1955.

[25] E.P. Hanavan, A mathematical model of the human body. AMRL-TR-64-102., AMRL-TR, Aerosp. Med. Res. Lab. (1964) 1–149.

[26] R. Baker, Pelvic angles: A mathematically rigorous definition which is consistent with a conventional clinical understanding of the terms, Gait Posture 13 (2001) 1–6, https://doi.org/10.1016/S0966-6362(00)00083-7.

[27] A. Carvalho, J. Vanrenterghem, S. Cabral, A. Assunção, A.P. Veloso, R. Fernandes, V. Moniz-Pereira, Markerless three-dimensional gait analysis in healthy older adults: test-retest reliability and measurement error, J. Biomech. 174 (2024) 112280, https://doi.org/10.1016/j.jbiomech.2024.112280.

[28] D. Meldrum, C. Shouldice, R. Conroy, K. Jones, M. Forward, Test-retest reliability of three dimensional gait analysis: including a novel approach to visualising agreement of gait cycle waveforms with Bland and Altman plots, Gait Posture 39 (2014) 265–271, https://doi.org/10.1016/j.gaitpost.2013.07.130.

[29] N. Stergiou, Innovative analyses of human movement. Analytical tools for movement research, Champaign, IL: Human Kinetics, 2004.

[30] P. Schober, C. Boer, L.A. Schwarte, Correlation coefficients: appropriate use and interpretation, Anesth. Analg. 126 (2018) 1763–1768, https://doi.org/10.1213/ANE.0000000000002864.

[31] M.A. Mansournia, R. Waters, M. Nazemipour, M. Bland, D.G. Altman, Bland-Altman methods for comparing methods of measurement and response to criticisms, Glob. Epidemiol. 3 (2021) 100045, https://doi.org/10.1016/j.gloepi.2020.100045.

[32] J.M. Bland, D.G. Altman, Measuring agreement in method comparison studies, Stat. Methods Med. Res. 8 (1999) 135± 160 Measuring. https://doi.org/10.1002/sim.5955.

[33] J. Røislien, L. Rennie, I. Skaaret, Functional limits of agreement: a method for assessing agreement between measurements of gait curves, Gait Posture 36 (2012) 495–499, https://doi.org/10.1016/j.gaitpost.2012.05.001.

[34] J.L. McGinley, R. Baker, R. Wolfe, M.E. Morris, The reliability of three-dimensional kinematic gait measurements: a systematic review, Gait Posture 29 (2009) 360–369, https://doi.org/10.1016/j.gaitpost.2008.09.003.

[35] S.D. Souza, T. Siebert, V. Fohanno, A comparison of lower body gait kinematics and kinetics between Theia3D markerless and marker- based models in healthy subjects and clinical patients, Sci. Rep. 14 (2024) 1–14, https://doi.org/10.1038/s41598-024-80499-8.

[36] M.P. Kadaba, H.K. Ramakrishnan, M.E. Wootten, J. Gainey, G. Gorton, G.V. B. Cochran, Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait, J. Orthop. Res. 7 (1989) 849–860, https://doi.org/10.1007/978-1-4471-5451-8_101.

[37] B. Horsak, A. Eichmann, K. Lauer-Maier, K. Prock, B. Dumphart, Concurrent assessment of a smartphone-based markerless and marker-based motion capture system in pathological gait, Gait Posture 106 (2023) S79–S80, https://doi.org/10.1016/j.gaitpost.2023.07.098.

[38] A. Baudet, C. Morisset, P. D'Athis, J.F. Maillefert, J.M. Casillas, P. Ornetti, D. Laroche, Cross-talk correction method for knee kinematics in gait analysis using principal component analysis (PCA): A new proposal, PLOS One 9 (2014) 1–7, https://doi.org/10.1371/journal.pone.0102098.

[39] H. Tang, J. Pan, B. Munkasy, K. Duffy, L. Li, Comparison of lower extremity joint moment and power estimated by markerless and marker-based systems during treadmill running, Bioengineering 9 (2022), https://doi.org/10.3390/bioengineering9100574.

[40] S.E. Kessler, M.J. Rainbow, G.A. Lichtwark, A.G. Cresswell, S.E. D'andrea, N. Konow, L.A. Kelly, A direct comparison of biplanar videoradiography and optical motion capture for foot and ankle kinematics, Front. Bioeng. Biotechnol. 7 (2019), https://doi.org/10.3389/fbioe.2019.00199.

[41] S. Bousigues, A. Naaim, T. Robert, A. Muller, R. Dumas, The effects of markerless inconsistencies are at least as large as the effects of the marker-based soft tissue artefact, J. Biomech. 182 (2025) 112566, https://doi.org/10.1016/j.jbiomech.2025.112566.

[42] J. Kearney, H. Greaves, M. Robinson, G. Barton, K. Gibbon, T. O'Brien, D. Wright, O. Pinzone, R. Foster, Changes in trunk and lower body gait kinematics in children following a Theia3D update. Gait Posture, Elsevier, 2024, pp. 113–114, https://doi.org/10.1016/j.gaitpost.2024.07.127.