The inter-trial and inter-session reliability of markerless gait analysis in tight versus loose clothing (#102339)

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The inter-trial and inter-session reliability of markerless gait analysis in tight versus loose clothing

Sylvia Augustine Corresp., 1 , **Richard J Foster** 1 , **Gabor J Barton** 1 , **Mark J Lake** 1 , **Raihana Sharir** 1, 2 , **Mark A Robinson** Corresp. 1

1 School of Sport and Exercise Sciences, Liverpool John Moores University, Liverpool, United Kingdom

2 Faculty of Sports Science and Recreation, Universiti Teknologi MARA (UiTM), Shah Alam, Selangor, Malaysia

Corresponding Authors: Sylvia Augustine, Mark A Robinson
Email address: s.b.augustine@2021.ljmu.ac.uk, m.a.robinson@ljmu.ac.uk

Background

Gait analysis is traditionally conducted using marker-based methods yet markerless motion capture is emerging as an alternative. Initial studies have begun to evaluate the reliability of markerless motion capture yet the evaluation of different clothing conditions across sessions and complete evaluation of the lower limb and pelvis reliability have yet to be considered. The aim of this study was to evaluate the inter-trial, inter-session and inter-session-clothing variation and root mean square differences between tight- or loose-fitting clothing during walking.

Method

Twenty-two healthy adult participants walked along an indoor walkway whilst eight video cameras recorded their gait in either tight- or loose-fitting clothing. A commercial markerless motion capture system (Theia3D) provided gait kinematics for evaluation.

Results

Reliability results showed average inter-trial variation of <2°, inter-session variation of <3° and inter-session-clothing variation <3.5°. RMSD between clothing conditions were <2°.

Discussion

Pelvis variations were smaller than those at the hip, knee and ankle. Our results showed smaller variation than in previous studies which may be due to updates to software. The demonstration of good reliability of markerless motion capture for gait analysis in healthy adults should prompt further evaluation in clinical scenarios and reconsideration of multi-assessor marker-based gait analysis protocols, where variation is highest.

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Sylvia Augustine[1], Richard J Foster[1], Gabor J Barton[1], Mark J Lake[1], Raihana Sharir[1,2] Mark A Robinson[1]

[1] School of Sport and Exercise Sciences, Liverpool John Moores University, Liverpool United Kingdom
[2] Faculty of Sports Science and Recreation, Universiti Teknologi MARA (UiTM), Shah Alam Selangor, Malaysia

Corresponding Author:
Mark A Robinson[1]
Byrom Street, Liverpool, L3 3AF United Kingdom.
Email address: m.a.robinson@ljmu.ac.uk

Abstract

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Introduction

Gait analysis is a common procedure used in both clinical and research settings. Typical gait analysis examines kinematics at the pelvis, hip, knee, and ankle in one complete gait cycle. Kinematics are routinely obtained by sticking reflective markers on to anatomical locations of participants which requires a trained tester. The position of these markers is captured by infra-red motion capture cameras in a laboratory setting to establish the kinematics of the participant as they walk. Careful placement of markers is crucial for accurate kinematic data (Riazati et al., 2022) and to minimise variation (Gorton III et al., 2009).

Variation in marker-based gait analysis can be attributed to different sources of experimental error (Schwartz et al., 2004). Intrinsic variation (or inter-trial variation) describes the natural repeatability of gait patterns including fluctuations in walking speed, whereas extrinsic variation (or inter-session variation) adds the effects of repeating the experimental process on to the inter-trial variation. Variation in marker-based gait measurement have been comprehensively examined with differing variation seen between joints, models and planes (see McGinley et al. 2009 for a review). Their synthesised summary provided the suggestions that gait kinematic variation <2° might be "acceptable", variation between 2-5° might be "reasonable" and >5°

degrees may “raise concern”. The Clinical Movement Analysis Society UK and Ireland CMAS, (Stewart et al., 2023) also provide guideline thresholds of 5° for intra-tester repeatability. Although these are global thresholds, that may not universally be accepted, they are a useful benchmark to evaluate new technologies ~~against~~.

Markerless motion capture is an attractive alternative to marker-based motion capture because it can also generate kinematics whilst potentially mitigating some of the errors with placing markers (Colyer et al., 2018). Markerless motion capture hardware/software systems range from single to multi-camera approaches (Wade et al., 2022) e.g. Microsoft Kinect, Captury, SIMI motion capture, OpenPose, DeepLabCut, Theia3D, OpenCap, and each has their own merits and limitations. This study specifically considers Theia3D (Theia Markerless Inc., Kingston, ON, Canada) as a leading commercial system which was available to us. Theia3D uses deep-learning-algorithms to recognize important anatomical features from multiple 2D videos to create a three-dimensional (3D) inverse kinematic pose of body segments (Kanko et al., 2021c). As segmental kinematics are determined algorithmically, markers are not physically placed on participants and therefore markerless motion capture may not be susceptible to the same errors as marker-based motion capture.

Initial studies have begun to evaluate the reliability of Theia3D for gait analysis, with specific consideration of spatiotemporal parameters (Kanko et al., 2021c; McGuirk et al., 2022; Riazati et al., 2022), non-pathological gait (Kanko et al., 2021b; Riazati et al., 2022) different clothing types (Keller et al., 2022) and pathological gait (McGuirk et al., 2022; Outerleys et al., 2024). Results to date show average inter-trial variation across planes and joints appear to be within reasonable limits at 2.5° (McGinley et al., 2009) with inter-session variation increasing average variation to 2.8° (Kanko et al., 2021a) and 2.85° (Riazati et al., 2022). Averages though can mask higher variation in particular joints, planes and times, as transverse plane results had higher variation than other planes (Kanko et al., 2021a; Riazati et al., 2022). What is notably absent in the above studies however is consideration of the repeatability of the pelvis kinematics. Pelvis kinematics are typically reported in all planes during a gait analysis to inform clinical decision making about surgical interventions and are 3/9 angle inputs of the gait indices (Schwartz et al., 2008; Barton et al., 2012). The reliability of pelvis kinematics should therefore also be determined.

The initial markerless reliability studies using Theia3D (Kanko et al., 2021a; McGuirk et al., 2022; Riazati et al., 2022) deliberately made no attempt to control the clothing worn by participants. As Theia3D identifies anatomical features, different clothing may affect landmark identification and therefore joint kinematics. We are only aware of one study (Keller et al., 2022) to date that has evaluated the effect of clothing on the reliability of gait kinematics. In their comparison of “sport” and “street” clothing average RMSD of 2.6° across all joints and planes was observed, and a range of 1.4° (frontal plane hip) to 4.2° (ankle in-out toeing) reported. Their clothing evaluation occurred within the same session, yet a likely gait analysis situation is also where participants return on a separate day in different clothing. The variation associated with a combination of a second session and altered clothing, what we subsequently call the inter-session-clothing variation, should therefore be quantified.

This study aims to (1) evaluate the inter-trial and inter-session gait variation including pelvis kinematics, (2) evaluate the effect of clothing within and between sessions.

Materials & Methods

Participants

A convenience sample of 22 healthy participants (8=male, 14=female, mean±SD age: 25±4 years; height 174±9 cm, 70±11, body-mass-index: 22±5 kg/m^2) volunteered for this study. Participants were free from lower-limb injury, not undergoing rehabilitation and without neuromuscular or musculoskeletal impairment. All participants provided informed consent and the study was granted Liverpool John Moores University Research Ethics Committee approval (UREC reference: 21/SPS/063).

Protocol

Participants attended the biomechanics laboratory for two gait data capture sessions, with the second session within 14 days of the first. For gait evaluation, participants completed five separate overground walks at a self-selected preferred pace through a 6m long x 3m wide calibrated volume. Participants brought 2 sets of clothing for each session. One set was "tight" e.g. a base layer or tight-fitting top exposing the elbow and tight shorts above the knee that would follow body movements. Participants were advised to wear contrasting colours between the top and shorts to avoid participants wearing only one colour of clothing. The second set was "loose" which was loose-fitting regular daily wear without constraints. Participants were required to wear same pair of shoes for both sessions (Figure 1). Five trials in each clothing condition were completed. Video data were captured using eight synchronized Qualisys Miqus video cameras (Qualisys AB, Gothenburg, Sweden) with a resolution of 1280 x 720 pixels and capture rate of 180 Hz. Cameras were positioned on tripods around the walking volume and closer to the volume centre than what would be typical for a 3D camera system to ensure that the participant was at least 500 pixels tall within the calibrated volume.

Data Analysis

Video data were processed using Theia3D software (Theia Markerless Inc., Kingston, ON, Canada, v2022.1.0.2309) which generated their default full-body model. The default model has a six degrees-of-freedom at the pelvis and three rotational degrees-of-freedom at the hip, knee and ankle (Kanko et al., 2021a). Model pose estimation generates 4x4 pose matrices for each segment for all frames using inverse kinematics, smoothed at 10 Hz with a low-pass GVCSPL filter. The filtered Theia3d data was saved as a c3d file and taken into Visual 3D (v.5.02.30, C-Motion, Germantown, MD, USA) for further kinematic analysis.

Toe off and heel strike events were defined as the maximal displacement of the heel and toe from the sacrum (Zeni et al., 2008). Pelvis, hip, knee and ankle joint angles for a single rightsided gait cycle were calculated in Visual 3D. Separate trials were collected to ensure that inter-trial variation represented completely separate walking trials, as would typically be collected during a gait analysis, rather than collecting multiple strides within the same walking trial where one stride might influence a subsequent stride. Gait kinematics for each trial, session and clothing condition were extracted for right foot heel strike to the next right foot heel strike, then linearly normalized to 101 points and exported to MATLAB2022a (The MathWorks, Natick) for further calculations.

Inter-trial, inter-session and inter-session-clothing variation were calculated across the gait cycle (Schwartz et al., 2004). We utilize the terminology of Kanko et al. (2021a) referring to "variation" rather than "error" with inter-trial variation representing intrinsic variation and inter-session and inter-session-clothing variation representing extrinsic variation, the combination of which contribute to total variability. Inter-trial variation was calculated from the five trials collected during the first test session. Inter-session variation was calculated using the five trials collected during both the first and second sessions for each clothing condition. Inter-session-clothing variation was calculated from all sessions and both clothing conditions (Figure 2). Variability ratios were calculated as the inter-trial variation divided by the inter-session variation. Summary metrics (averages, maxima, minima and ranges) were calculated from the inter-trial and inter-session variation. The average Root Mean Square Difference (RMSD) was also calculated to describe the average absolute difference between clothing conditions.

Results

Minimal inter-trial or inter-session variation differences were observed between clothing conditions (Figure 3). Inter-trial variation (one day, same clothes), when averaged across stance, joints and planes, were very similar between clothing conditions; loose clothing (1.35 ± 0.43°) had a slightly greater variation than tight clothing (1.29 ± 0.48°). Considering planes and joints separately, average inter-trial variation was <2° (Table 1). Peak inter-trial variation from single instances in the gait cycle reached magnitudes of 3.84° and 2.86° in the sagittal plane for the knee and ankle respectively (Table 2).

Inter-session variation (different days, different clothes, same clothes type), when averaged across stance, joints and planes, were also similar between clothing conditions; loose clothing (2.00 ± 0.56°) again had a slightly greater variation than tight clothing (1.88 ± 0.65°). Notably a second session increased variation by <1° Considered separately, average inter-session variation was <3° (Table 1). Peak inter-session variation from single instances in the gait cycle reached magnitudes of 3.77° and 3.57° in the sagittal plane for the knee and ankle respectively (Table 2). Average variation ratios were 1.51 for loose clothing and 1.49 for tight clothing indicating a second session increased total variation by around 50% (Table 3).

Inter-session-clothing variation (different days, clothes, clothes type) averaged across gait cycle, joints and planes were 2.35 ± 0.61°. Considered separately, the knee (3.41°) and hip (2.98°) transverse planes had the highest average variation. The peak inter-session-clothing variation occurred at the hip (4.48°) and knee (3.82°) in the sagittal plane.

Root mean square differences between the clothing conditions were <2° across all joints and planes (Figure 4). The highest RMSD was reported at 1.91° which was hip flexion/extension and the lowest RMSD was 0.89° for pelvic anterior/posterior tilt.

Discussion

The aims of this study were to evaluate markerless inter-trial and inter-session gait variation including pelvis kinematics and to evaluate the effect of clothing within and between sessions. Average inter-trial variation was <2°, inter-session variation was <3°, inter-session-clothing variation <3.5° and RMSD between clothing conditions were <2°.

Inter-trial and inter-session variation in this study were lower than reported in other markerless studies (Kanko et al., 2021a; Keller et al., 2022) and similar to marker-based studies (Schwartz et al., 2004; Manca et al., 2010; Kaufman et al., 2016). Inter-session variation with same clothing added an average of 1° variations. Variability of these magnitudes are "acceptable" and "reasonable" when compared to the suggested thresholds of variation expected for marker-based motion capture (McGinley et al., 2009). Variability was also below the 5° intra-tester threshold of CMAS ((Stewart et al., 2023). Multiple independent studies now show encouraging inter-trial and inter-session reliability using markerless gait analysis. It is important to not only consider summarized variations but also the key features of gait kinematic curves beyond maxima, minima and ranges of motion (Riazati et al., 2022). Studies comparing features to marker-based gait analysis are now emerging.

As no markers are placed on participants, and kinematics are determined algorithmically, inter-assessor variation does not apply to markerless analysis. This is significant as interassessor variation is generally greater than inter-trial and inter-session variation (Schwartz et al., 2004; Manca et al., 2010). As CMAS thresholds are 5-10° for inter-assessor variation, different criteria and quality assurance should instead be considered for markerless protocols. To extend this to practical contexts, gait labs with multiple assessors may wish to consider markerless gait analysis as a way to avoid the increase in inter-assessor variation that a second gait analysis provides. Firstly though, additional studies considering clinical populations and children (e.g. (McGuirk et al., 2022; Wren et al., 2023; Outerleys et al., 2024) are required. Differences in inter-laboratory variation (see (Kaufman et al., 2016) would also likely be reduced when using the same markerless software, but this is yet to be determined empirically.

As this is the first time the reliability of markerless pelvis kinematics have been evaluated, pelvis variation warrants specific consideration. Pelvis kinematic variations were generally smaller than the other joints which is consistent with marker-based studies (Schwartz et al., 2004; Manca et al., 2010; Kaufman et al., 2016). In markerless pose estimation, low pelvis variation could be because the pelvis is modelled as a six-degree of freedom segment. The pelvis is therefore independent of pose requirements of other segments in the inverse-kinematic chain. It could also be the case that pelvis landmarks are more consistently identified algorithmically but this is not known. With respect to specific gait features the tight clothing condition appeared to most appropriately represent the obliquity in the frontal plane whereas in the loose clothing condition the frontal plane of the pelvis remained relatively neutral. It remains to be seen therefore if pathological movement of the pelvis can be described appropriately in loose clothing if a greater reliance is placed on algorithmic determination of pelvis kinematics which may or may not be included in the model training.

The average variation ratios of ~1.5° for all joints and planes was notably higher than reported by Kanko et al. (2021) of ~1.1°. (Kanko et al., 2021a). This is due to the smaller inter-trial variation seen in this study which when considered against the additional ~1° inter-session variation, leads to a larger overall ratio. A second session therefore increases the variation in joint kinematics by ~50% irrespective of whether tight or loose clothing is worn. Nevertheless, this is still substantially smaller than variation ratios when a second assessor is involved (Schwartz et al., 2004). Reductions in inter-trial (intrinsic) variation could be caused by a newer software version used in this study, this is discussed below.

The average RMSD found between clothing conditions was actually smaller in this study 1.4° vs 2.6° (Keller et al., 2022). The choice of tight versus loose clothing did not affect the inter-trial or inter-session variation. The higher variation in the transverse plane remains a consistent result with previous studies but lower variation overall means that these are now comparable with the sagittal plane in other studies (Kanko et al., 2021a; Keller et al., 2022; Riazati et al., 2022). Higher transverse plane variation (hip and knee) is also commonly reported in marker-based motion analysis (Kanko et al., 2021b; Riazati et al., 2022). The lack of difference between clothing conditions could be due to the deep learning algorithm being trained on publicly available images in a variety of clothing (Kanko et al., 2021a). The obvious benefits of wearing tight clothing when placing skin-mounted markers on the body does not seem to contribute to any substantial reduction in variation compared to loose fitting clothing.

Inter-session-clothing variation was calculated to quantify the variation across sessions when participants wear different clothes (tight or loose). As it was calculated as a combination of the variation in both clothing conditions, an average variation of 2.35° approaches the most rigorous thresholds for marker-based data (McGinley et al., 2009). This is somewhat remarkable given it is an accumulation of inter-trial, inter-session and inter-clothing variations. It would therefore seem unnecessary for participants to change from everyday clothing into tighter fitting clothing for the purposes of markerless gait analysis. It should be noted however that more challenging clothing (e.g. a Jubah/thobe, long skirts, dresses) and accessories (e.g. backpacks) are untested to date.

Inter-trial and inter-session variation was lower than in previous studies. As Theia3D software provides pose data based on identified features, any updates to the software may result in altered kinematics between versions. Previous reliability studies have used earlier version of the software (Kanko et al., 2021a)- unknown; (Keller et al., 2022)- v.2021.1.0.1450; (Riazati et al., 2022)-v.2021.2.0.1675). This study used v2022.1.0.2309 which has resulted in lower inter-trial and inter-session variation and smaller differences between clothing conditions. Although we can only speculate that this could be due to version updates, it is seemingly important to report versions used to monitor the change in gait kinematics as the software updates. For example, in March 2023 an update to the Theia software was described in a Theia blog (https://www.blog.theiamarkerless.ca/) which, amongst other changes, increased the number of tracked landmarks compared to the earlier versions and may continue to reduce variation. Although it is not thought possible to reduce intrinsic variation of markerbased data (Schwartz et al., 2004) this could be possible through algorithmic updates to the inverse-kinematic modelling. Careful monitoring of updates should also take place to ensure reductions in variation do not lead to increased centralization of data or the redistribution of variation into other planes.

Limitations of this study are that there was some variation in clothing conditions as some participants wore loose fitting shorts and t-shirts as their choice of regular wear and therefore had exposed knees and elbows, and there was variation in the contrasting nature of the clothing worn. Although specific colours were not specified, colour contrast and contrast to the video background may be important to identify the anatomical features (Kanko et al., 2021a). Secondly, we considered right side gait data only. Thirdly these results are specific to the software version used for analysis. Since our analysis further updates to software have been released.

Conclusions

Variation in markerless motion capture data was within suggested thresholds of reliability for healthy adults. Specific consideration of the pelvis within this study found variation to be smaller than that of the hip, knee and ankle. Inter-session-clothing variation was <3.5° which suggests that the choice of clothing across multiple sessions does not increase variation substantially. Lower variation than in previous studies may be a result of continued algorithm development. As markerless technologies continue to demonstrate their reliability for healthy adult gait analysis, extending these studies to other populations and clinical context is now required.

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Figure 1

Example tight- and loose-fitting clothing for six participants.

Figure 2

Example sagittal plane hip angles to illustrate the calculation of inter-trial, inter-session and inter-session-clothing variation and summary metrics (St.Dev. = standard deviation, avg = average, max = maxima).

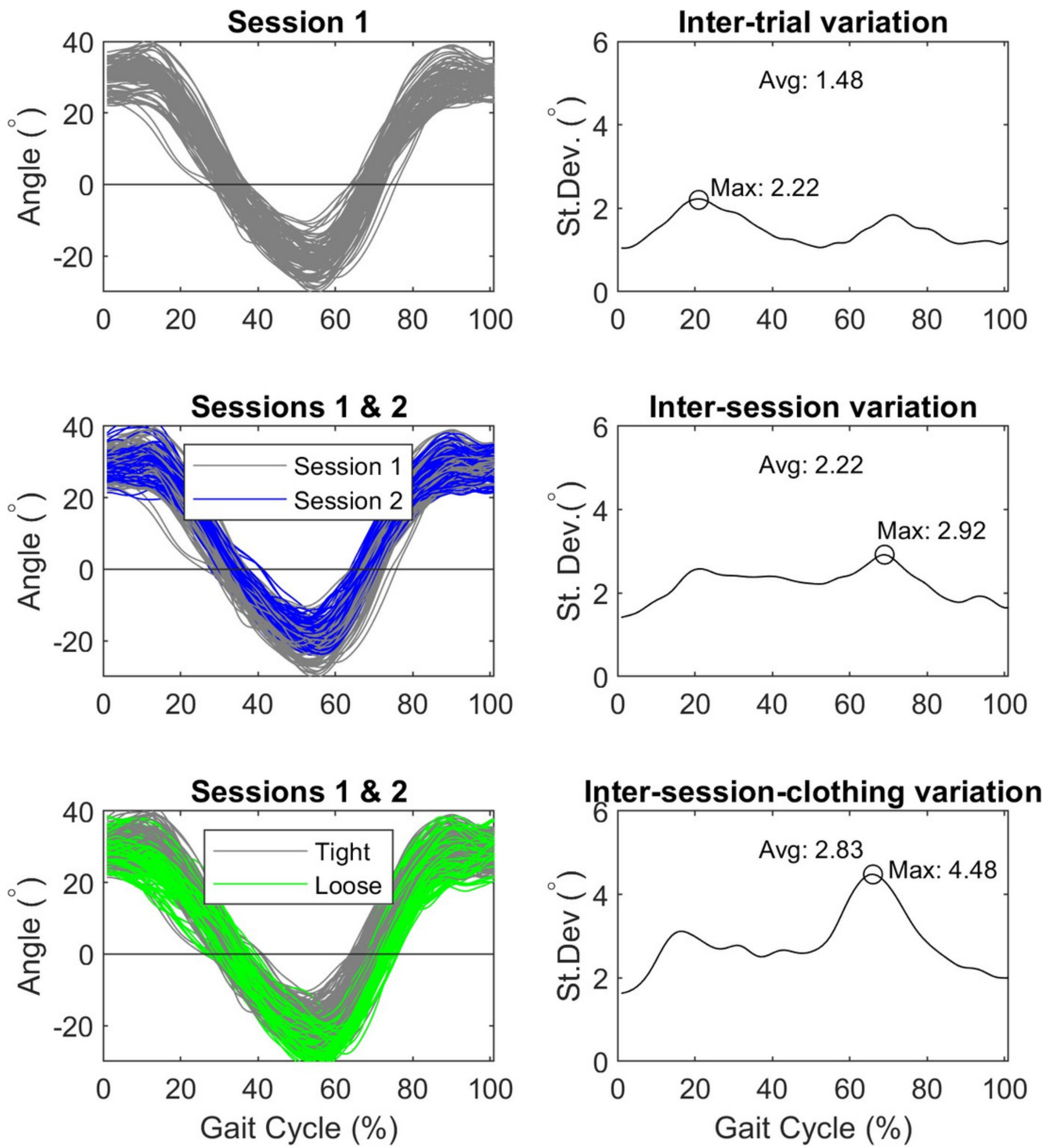
Session 1
Inter-trial variation
Avg: 1.48
Max: 2.22
Sessions 1 & 2
Session 1
Session 2
Inter-session variation
Avg: 2.22
Max: 2.92
Sessions 1 & 2
Tight
Loose
Inter-session-clothing variation
Avg: 2.83
Max: 4.48
Angle (°)
St.Dev. (°)
Gait Cycle (%)

Figure 3

Inter-trial and inter-session variation in sagittal, frontal and transverse plane lower-limb and pelvis kinematics. Solid lines represent loose clothing, dashed lines represent tight clothing

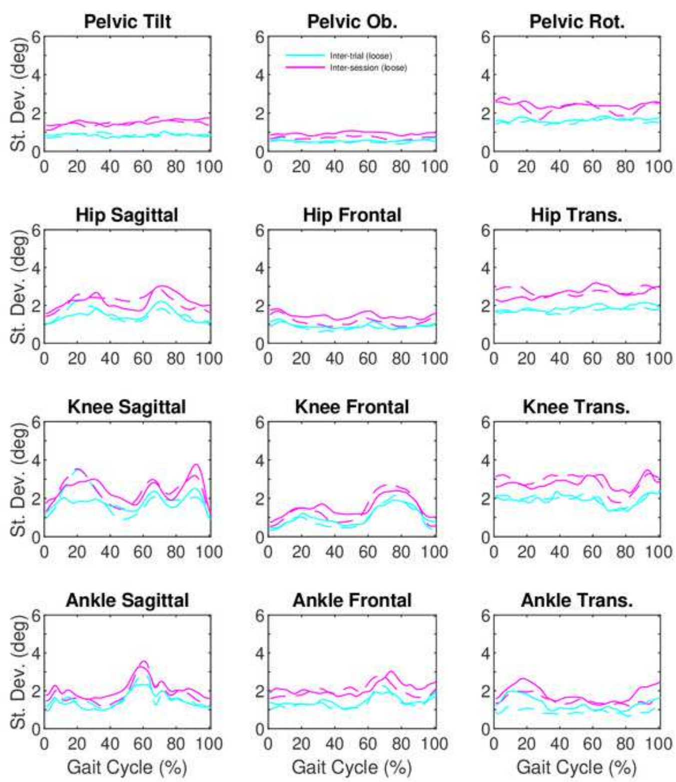
Pelvic Tilt
Pelvic Ob.
Pelvic Rot.
Inter-trial (loose)
Inter-session (loose)
Hip Sagittal
Hip Frontal
Hip Trans.
Knee Sagittal
Knee Frontal
Knee Trans.
Ankle Sagittal
Ankle Frontal
Ankle Trans.
St. Dev. (deg)
Gait Cycle (%)

Figure 4

Session one means and standard deviations (shaded) between the two types of clothing and Root Mean Square Difference (RMSD) between the clothing conditions is inset for each.

The green line represents loose clothing, and black line represent tight clothing

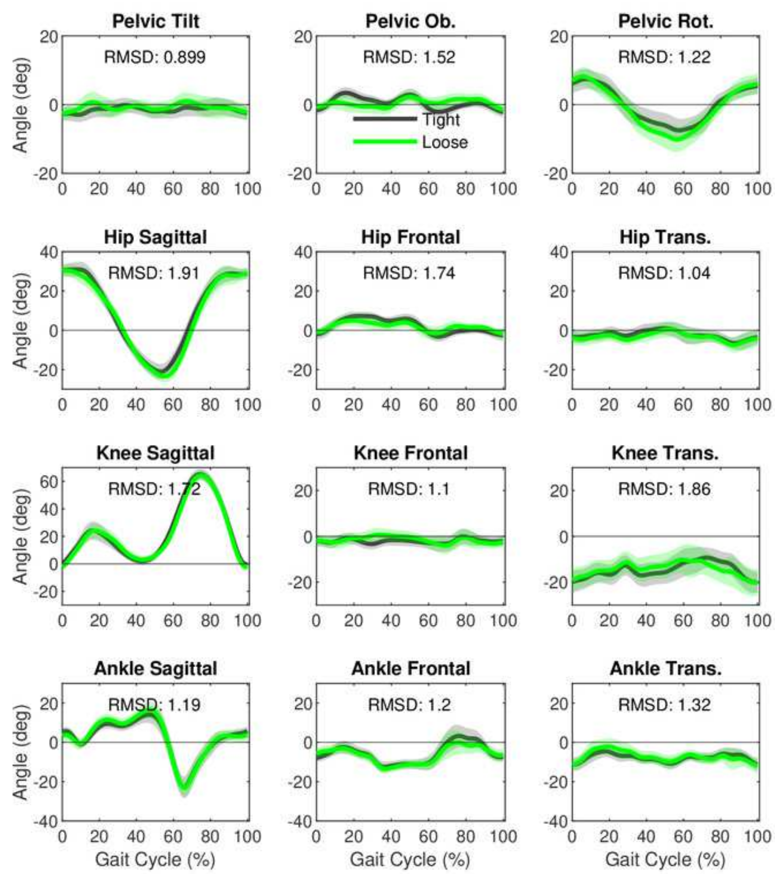
Pelvic Tilt
RMSD: 0.899
Pelvic Ob.
RMSD: 1.52
Tight
Loose
Pelvic Rot.
RMSD: 1.22
Hip Sagittal
RMSD: 1.91
Hip Frontal
RMSD: 1.74
Hip Trans.
RMSD: 1.04
Knee Sagittal
RMSD: 1.72
Knee Frontal
RMSD: 1.1
Knee Trans.
RMSD: 1.86
Ankle Sagittal
RMSD: 1.19
Ankle Frontal
RMSD: 1.2
Ankle Trans.
RMSD: 1.32
Angle (deg)
Gait Cycle (%)

Table 1 (on next page)

Average inter-trial, inter-session and inter-session-clothing variation

1 Table 1. Average inter-trial, inter-session and inter-session-clothing variation

	Sagittal		Frontal		Transverse	
	Loose	Tight	Loose	Tight	Loose	Tight
Average inter-trial variation (°)						
Pelvis	0.84	0.85	0.55	0.50	1.64	1.55
Hip	1.48	1.48	0.92	0.83	1.86	1.74
Knee	1.79	1.90	1.04	0.97	1.89	1.96
Ankle	1.49	1.52	1.44	1.35	1.31	0.88
Average inter-session variation (°)						
Pelvis	1.52	1.47	0.93	0.70	2.41	2.27
Hip	2.22	2.22	1.45	1.14	2.65	2.72
Knee	2.45	2.40	1.53	1.44	2.80	2.84
Ankle	2.07	1.84	2.11	2.00	1.83	1.50
Avg. inter-session-clothing variation(°)						
Pelvis	1.88		1.36		2.72	
Hip	2.83		1.77		2.98	
Knee	2.82		1.75		3.41	
Ankle	2.26		2.45		1.98	

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Table 2(on next page)

The range (Min-Max) for inter-trial, inter-session and inter-session-clothing variation

Table 1 The range (Min-Max) for inter-trial, inter-session and inter-session-clothing variation

	Sagittal		Frontal		Transverse	
	Loose	Tight	Loose	Tight	Loose	Tight
Range of inter-trial variation (°)						
Pelvis	0.71 - 1.00	0.68 – 1.03	0.39 – 0.73	0.47 – 0.71	1.32 – 1.73	1.43 – 1.84
Hip	1.04 – 2.23	1.00 – 2.22	0.60 – 1.14	0.75 – 1.27	1.46 – 1.89	1.59 – 2.14
Knee	0.89 – 3.84	0.92 – 2.51	0.33 – 2.15	0.45 – 1.90	1.34 – 2.39	1.32 – 2.38
Ankle	0.89 – 2.86	0.96 – 2.33	1.02 – 2.27	1.01 – 2.01	0.65 – 1.16	0.89 – 1.98
Range of inter-session variation (°)						
Pelvis	1.29 – 1.74	1.10 – 1.79	0.80 – 1.07	0.54 – 0.82	2.21 – 2.61	1.66 – 2.82
Hip	1.57 – 3.02	1.42 – 2.92	1.23 - 1.81	0.87 - 1.69	2.21 – 3.19	2.41 – 3.07
Knee	1.26 – 3.77	1.25 – 3.54	0.75 – 2.40	0.54 – 2.70	2.28 – 3.48	1.78 – 3.28
Ankle	1.54 – 3.27	1.17 – 3.57	1.70 – 3.03	1.60 – 2.80	1.25 – 2.65	1.18 – 1.98
Range of inter-session-clothing variation (°)						
Pelvis	1.48 – 2.39		1.08 – 1.92		2.06 – 3.36	
Hip	1.63 – 4.48		1.47 – 2.20		2.76 – 3.26	
Knee	1.72 – 3.82		0.80 – 2.83		2.92 – 3.77	
Ankle	1.68 – 3.65		2.01 – 3.24		1.47 – 2.94	

Table 3(on next page)

Average variation ratios for clothing conditions and joints

Table 3. Average variation ratios for clothing conditions and joints

	Sagittal		Frontal		Transverse	
	Loose	Tight	Loose	Tight	Loose	Tight
Pelvis	1.81	1.73	1.72	1.43	1.47	1.48
Hip	1.51	1.54	1.59	1.38	1.42	1.57
Knee	1.37	1.33	1.54	1.54	1.5	1.45
Ankle	1.41	1.21	1.48	1.52	1.41	1.71