applied sciences

Article

# Investigating the Effect of Motion Capture Suits on the Test–Retest Reliability of Gait Parameters

**Matt C. Smith [1,*], Phaedra Leveridge [2], Garry Massey [2], Jessica Tyrrell [3], Malcolm Hilton [4] and Genevieve K. R. Williams [2]**

[1] Department of Biomedical and Clinical Sciences, Public Health and Sports Sciences Department, University of Exeter Medical School, Exeter EX1 2HZ, UK
[2] Public Health and Sports Sciences Department, University of Exeter Medical School, Exeter EX1 2HZ, UK; pkll201@exeter.ac.uk (P.L.); g.j.massey@exeter.ac.uk (G.M.); g.k.r.williams@exeter.ac.uk (G.K.R.W.)
[3] Genetics of Complex Traits, Department of Biomedical and Clinical Sciences, Faculty of Health and Life Sciences, University of Exeter, Exeter EX4 4QJ, UK; j.tyrrell@exeter.ac.uk
[4] Clinical and Biomedical Science, University of Exeter Medical School, Exeter EX1 2LU, UK; m.hilton@exeter.ac.uk
* Correspondence: ms893@exeter.ac.uk

**Abstract:** When collecting marker-based motion capture data from clinical populations, speed of collection and comfort for the participant is a priority. This could be achieved by attaching markers to motion capture Velcro suits, as opposed to the skin. This study aimed to ascertain the reliability of sagittal-plane gait parameters estimated using Plug-in Gait (PiG) and Conventional Gait Model 2 (CGM2) marker sets from data collected in Suited and Non-suited (markers placed onto skin) conditions. For ten participants, markers were placed based on PiG and CGM2 models and data captured during a 2-min treadmill walk. Trials were repeated in suited and non-suited conditions. PiG ankle flexion/extension measurements had poor/moderate reliability (Non-suited ICC = 0.531, Suited ICC = 0.435). CGM2 ankle flexion/extension measurements had good/excellent reliability (Non-suited ICC = 0.916, Suited ICC = 0.900). There were significant differences in minimal detectable change (MDC) between conditions at the ankle for PiG (Non-suited MDC = 2.32°, Suited MDC = 18.90°), but not for CGM2 (Non-suited MDC = 0.63°, Suited MDC = 0.95°). When using CGM2, knee (Non-suited ICC = 0.878, Suited ICC = 0.855) and hip (Non-suited ICC = 0.897, Suited ICC = 0.948) showed good/excellent reliability in both conditions. A motion capture suit is not a reliable solution when collecting joint angle data using the PiG model but is reliable enough to consider when using the CGM2 model.

**Keywords:** motion capture; intraclass correlation; minimal detectable change; gait analysis; clinical biomechanics

check for updates

**Citation:** Smith, M.C.; Leveridge, P.; Massey, G.; Tyrrell, J.; Hilton, M.; Williams, G.K.R. Investigating the Effect of Motion Capture Suits on the Test–Retest Reliability of Gait Parameters. *Appl. Sci.* **2024**, *14*, 8570. https://doi.org/10.3390/app14188570

Academic Editor: Arkady Voloshin

Received: 22 August 2024
Revised: 18 September 2024
Accepted: 20 September 2024
Published: 23 September 2024



## 1. Introduction

Working with clinical populations, we are interested in collecting kinematic data in the quickest, easiest, and least invasive manner possible to maximise participant comfort. In doing so, the first aspect to consider is the model and marker set used. This has large implications as to the length of the data collection process for participants and researchers. A systematic review of 23 articles [1] showed that the Plug in Gait (PiG) is a commonly used and reliable model for simple gait analysis in the sagittal plane [2]. PiG was originally designed to offer a relatively minimal marker set for use with clinical populations [3]. PiG has shown good to excellent reliability in the sagittal plane, comparable to the more complex and computationally expensive conventional gait model 2 (CGM2) [4].

When using marker-based motion capture systems (MOCAP), markers are best placed directly onto the skin to minimise error associated with clothing and soft tissue movement [4]. Markers are fixed to participants using single use tape. Attaching markers with tape is not only time consuming but is associated with skin abrasion and rashes in older populations [5]. In addition, when taped to the skin, markers can fall off during dynamic tasks.

MOCAP suits are used in the animation industry, where time efficiency is more important than anatomical accuracy. The suits are skin-tight and allow for markers to be attached via Velcro. The use of suits reduces the time taken to place markers and mitigates the risk of skin irritation associated with sticking markers to the skin. Therefore, these suits could be implemented in data collections, particularly when considering the feasibility of large-scale data clinical biomechanics studies with ageing and clinical populations [6]. Previous studies have used the kinematic data for ankle, knee and hip joints to investigate the possible causes of injury [7,8] and track intervention and rehabilitation protocols [9]. The ankle, knee and hip joints provide essential roles in gait and are able to modulate their stiffness in response to changes in load or task, which in turn can be used to increase metabolic efficiency in gait [10]. Changes from distal (ankle) to proximal (hip) shifts in joint workloads have also been observed with advancing age, with older individuals producing more power for walking from the hips than younger adults, again increasing the metabolic cost of walking [11]. The use of motion capture data can aid in monitoring these changes. With objective data to compare across multiple timepoints and the ability to corelate discrete joint metrics with other quantitative and qualitative measures, this data is invaluable for bio-mechanists and clinicians. Therefore, methods such as the use of a MOCAP suit would seem logical as they increase the ease and reduce the time associated with data collection, significantly increasing the number of individuals that can be tested in a set time frame. However, the test–retest reliability of key gait kinematic parameters, such as ankle, knee and hip joint angles, when placing markers onto MOCAP suits is unknown. Therefore, users of a MOCAP suit could not be confident in the reliability of the kinematic measures they receive across multiple tests and may not be able to discern the difference between changes in kinematic measures as a result of an intervention or as a result of errors caused by the suit.

Finally, in considering test–retest reliability of the PiG, it should be noted that the PiG may be vulnerable to marker misalignment, particularly at the foot [6]. However, there are several ways to define the foot segment using the PiG, which may negate the effect of marker misalignment and improve reliability. It is unclear whether the use of a suit or alternative definitions of the foot segment would impact the reliability of model outputs.

This study aimed to investigate the test–retest reliability of lower limb gait kinematics in the sagittal plane estimated based on the PiG and CGM2 marker set from data collected with motion capture suits compared to markers placed directly onto the skin. The purpose was to provide a reference for test–retest reliability that can be used by other studies using populations for which marker attachment directly to the skin is problematic.

This study also aimed to evaluate the use of an alternative foot definition to improve reliability and reduce known weaknesses of the PiG model related to reliability of ankle angles.

## 2. Materials and Methods

### 2.1. Participants

Ethical approval was obtained through the Sport and Health Sciences Ethics Committee at the University of Exeter. Ten participants were recruited based on the median sample size in studies reviewed by McGinley et al. (2009) [1]. Participants (60% female, average age = 25 $\pm$ 7 years, average BMI = Male: 23.6 kg/m$^2$; Female: 24.2 kg/m$^2$) gave voluntary, informed, written consent prior to data collection. Participants were required to have a BMI between 20 and 30 kg/m$^2$ and no current musculoskeletal injuries.

### 2.2. Protocol

Participants were asked to walk on a Motek R mill m-gait dual-belt instrumented treadmill [12] for 120 s at a set velocity of 1.5 m/s. Treadmill walking was chosen to allow for the collection of multiple gait cycles as opposed to collecting overground walking, which heavily restricts the number of gait cycles we can measure.

Participants completed 6 walking trials, during which markers were placed either in suited or unsuited conditions (three of each). The MOCAP suit given to each participant was of the appropriate size to ensure proper fitting and all participants were checked by the researcher to ensure proper fitting of the suit. The order of suited or non-suited trials was randomised. Static calibration trials lasting 10 s were captured before each walking trial with participants holding their arms up in a t-pose.

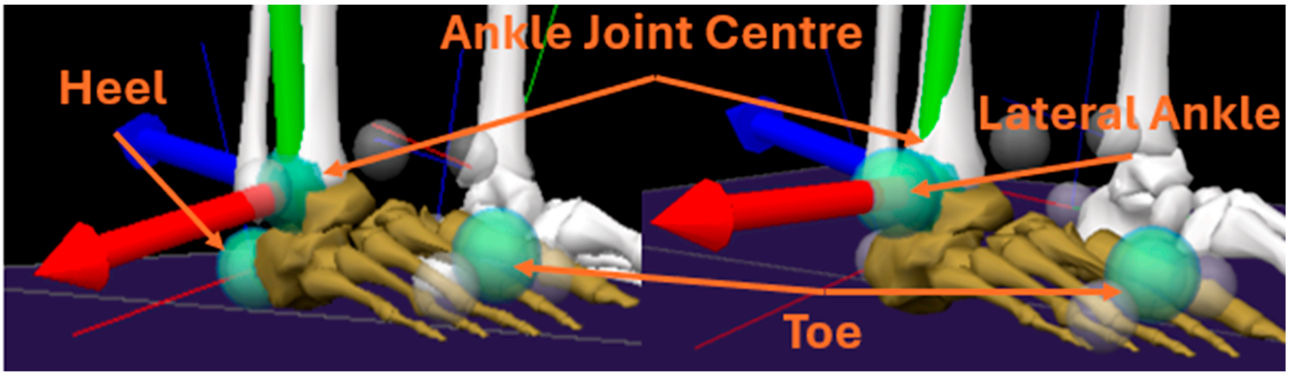
Markers were placed on their body according to the CGM2.3 model, with 55 markers either attached onto their skin (non-suited) or onto a Velcro suit (suited), with placement dictated by Vicon documentation [13]. The non-suited condition required participants to wear shorts and a skin-tight top. The suited condition required participants to wear both halves of an Optitrack MOCAP suit and slippers (NaturalPoint, Inc., Corvallis, OR, USA) in sizes best fitting the participant. Participants were checked to ensure the suit was worn properly by the researcher. Trainers were worn during all trials. Data were captured using a 12 camera Qualisys Miqus M3 system (200 Hz) [14]. Before and after each trial, markers were placed and removed. Rest periods were provided in order for any skin blemish from previous markers to fade. One researcher with ~2 years of MOCAP marking experience attached markers to the participants.

*2.3. Data Processing*

Raw marker data were processed in Qualisys Track Manager [14] with trials manually screened, markers labelled and exported to Visual3D (V3D) [15]. A model template based on the PiG model was built for each trial based on V3D guidance [16], which ignored any redundant markers that were placed on the body as required by the CGM2 model. A model template based on the CGM2.3 model was also built for each trial based on pycgm2 [3] and Vicon ProCalc guidance [17]. Unique model templates for each trial were constructed to ensure that differences in marker placement were also measured in static calibration files.

Raw marker positions were filtered using a low-pass, 4th order Butterworth filter at 6 Hz. A 3rd order polynomial gap filling was performed on all gaps in the data <10 frames. No gaps greater than 10 frames were present. Heel strike (HS) and toe-off (TO) were defined as described by Zeni et al. (2008) [18]. The start and end of each gait cycle was defined by the heel strike of the foot with each cycle normalised to 100%. Segments and joint centres were constructed and defined in V3D based on static standing trials. Ankle, knee and hip joint angles were defined as the orientation of the distal segment relative to the proximal segment. The cardan sequence xyz was used in line with ISB recommendations [19]. Discrete measures of left and right ankle, knee and hip joint flexion/extension angles were calculated at maximum (Max), minimum (Min), TO and HS of each gait cycle completed within the 120 s trial.

Two methods were used to define the ankle angle in the PiG model. Firstly, the standard PiG method was employed, as described by CMotion (2022) [16] (Figure 1a). Secondly, an alternative method defined the foot segment with the proximal joint centre as the ankle joint centre (AJC), the distal joint centre as the toe and the lateral ankle marker as the lateral marker to define the segment orientation (Figure 1b). Reliability of these two approaches were compared.




(**a**) (**b**)

**Figure 1.** (**a**) PiG foot segment definition using standard PiG instructions. The AJC is used as the proximal joint centre and the toe as the distal joint centre. The heel marker is then used as a posterior marker to define the orientation. Cone arrows indicate segment coordinate system. (**b**) Alternative foot segment definition. The AJC is used as the proximal joint centre and the toe as the distal joint centre. The lateral ankle marker is then used as a lateral marker to define the orientation. Cone arrows indicate segment coordinate system.

### 2.4. Statistical Analysis

For each participant, the mean and standard deviations (SD) of each metric (ankle, knee and hip angle at toe-off, heel-strike, maximum and minimum) for each leg was calculated from each trial, resulting in six values (left and right ankle, knee and hip) across the four metrics (HS, TO Max and Min). The SD of the means across the 3 trials was also calculated.

Intraclass correlation coefficient (ICC) values [20] were used as a measure of relative reliability. Interpretation of ICC values was conducted according to published guidance [21]. An ICC of less than 0.5 was considered poor, between 0.5 and 0.75 moderate, between 0.75 and 0.90 good and above 0.90 excellent [21]. The Minimal Detectable Change (MDC) is the minimal amount of change that would be accepted as a real change greater than that seen due to random variation or error [22]

The ICC (2) Two Way Random Effects [20] was calculated using the ICC function in SPSS (Version:29.0.0.0) [23] using the three mean values from each suited and non-suited trial. Standard error of measurement (SEM) was calculated using Equation (1) [24], after which MDC was calculated (Equation (2)).

$$SEm = SD(\sqrt{1 - ICC}) \tag{1}$$

SD = Standard deviation of the mean values across 3 trials
ICC = Intra Class Correlation Coefficient

$$MDC = SEm(1.96(\sqrt{2})) \tag{2}$$

ICCs and MDCs for each metric and average values over the four metrics were tabulated for each joint. Paired *t*-tests [25] were used to check for a statistically significant difference between the mean ICC and MDC of the suited and non-suited trials.

A paired *t*-test was used to identify if the alternative PiG foot segment definition made a difference in the ICC and MDC results. A result was considered significant if the *p* value was less than 0.05. A paired t-test was also used to identify whether the ICCs and MDC of joint angles were significantly different using the CGM2 model compared to the PiG.

## 3. Results

### *3.1. Ankle Angle Variables (Standard PiG Foot Definition)*

ICCs of the ankle angle were lower at HS, TO and Min in the suited trials compared to the non-suited. ICC values were highly varied in both non-suited (ranging between 0.254 and 0.743, for HS and TO, respectively) and suited trials (ranging between 0.238 and 0.575 for HS and Max, respectively). There was moderate reliability in non-suited trials with an average ICC across all four events (0.531) larger than that for the suited (0.435), which showed poor reliability (PDifference = 0.32) (Table 1) (Figure 2). It appears that, when using the PiG model, the HS measure was consistently bad across both suited and non-suited conditions. However, there were not enough measures to discern a robust association. This should be noted by those who are planning on using PiG for analysis of ankle measures during heel-strike events. CGM2 foot definition: ICC values in the CGM2 definition were significantly higher than the PiG definition (PDifference non-suited = 0.02; PDifference Suited < 0.01). The ICCs of the ankle angle were marginally higher in the non-suited condition at HS, TO and Max when compared to the suited condition, but not at Min (PDifference = 0.77) (Table 2). There was excellent reliability across all timepoints in the non-suited condition and excellent reliability at TO and Min in the suited condition, with HS and Max being good (ICC = 0.872; ICC = 0.878, respectively).

**Table 1.** Average ICC and MDC in Non-Suited and Suited trials at each joint across all events (PiG).

| Joint | ICC | | | MDC | | |
|---|---|---|---|---|---|---|
| | **Non-Suited** | **Suited** | ***p*-Value** | **Non-Suited** | **Suited** | ***p*-Value** |
| Ankle | 0.531 | 0.435 | 0.32 | 2.32 | 18.90 | 0.02 |
| Knee | 0.832 | 0.707 | 0.13 | 2.06 | 3.98 | 0.06 |
| Hip | 0.899 | 0.945 | 0.19 | 1.88 | 1.71 | 0.07 |

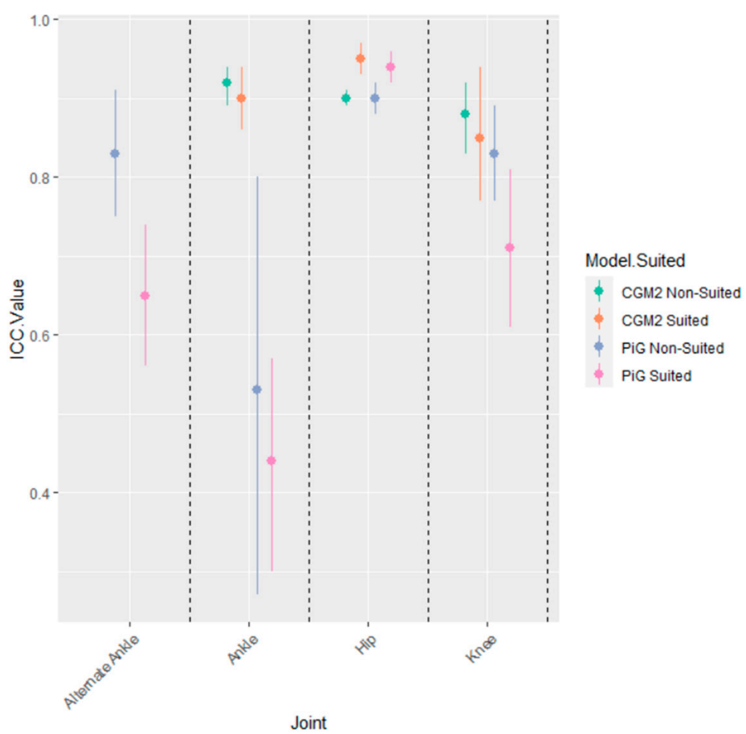



**Figure 2.** Mean and 95% Confidence intervals (CI) of ICC values for each joint (PiG ankle, alternative ankle, knee, hip and CGM2 ankle, knee and hip) and for both suited and non-suited conditions.

**Table 2.** Average ICC and MDC in Non-Suited and Suited trials at each joint across all events (CGM2).

| Joint | ICC | | | MDC | | |
|---|---|---|---|---|---|---|
| | **Non-Suited** | **Suited** | ***p*-Value** | **Non-Suited** | **Suited** | ***p*-Value** |
| Ankle | 0.916 | 0.900 | 0.77 | 0.63 | 0.95 | 0.08 |
| Knee | 0.878 | 0.855 | 0.90 | 1.20 | 2.32 | 0.16 |
| Hip | 0.897 | 0.948 | 0.541 | 1.35 | 1.42 | 0.46 |

The MDC in the PiG definition was significantly lower in the non-suited (average 2.33°) compared to the suited (average 18.90°) trials ($p$ = 0.02; Table 1). The MDC of the ankle angle in the non-suited trials was over 8-fold smaller than the MDC of the ankle angle in the suited trials (Figure 3). MDC values in the CGM2 were again significantly lower than the MDC values in the PiG (PDifference non-suited < 0.01; PDifference suited = 0.03) (Figure 3). There was, however, no difference in the MDC between suited (MDC = 1.21°) and non-suited (MDC = 0.63°) trials when looking solely at the CGM2 definition (PDifference = 0.08).

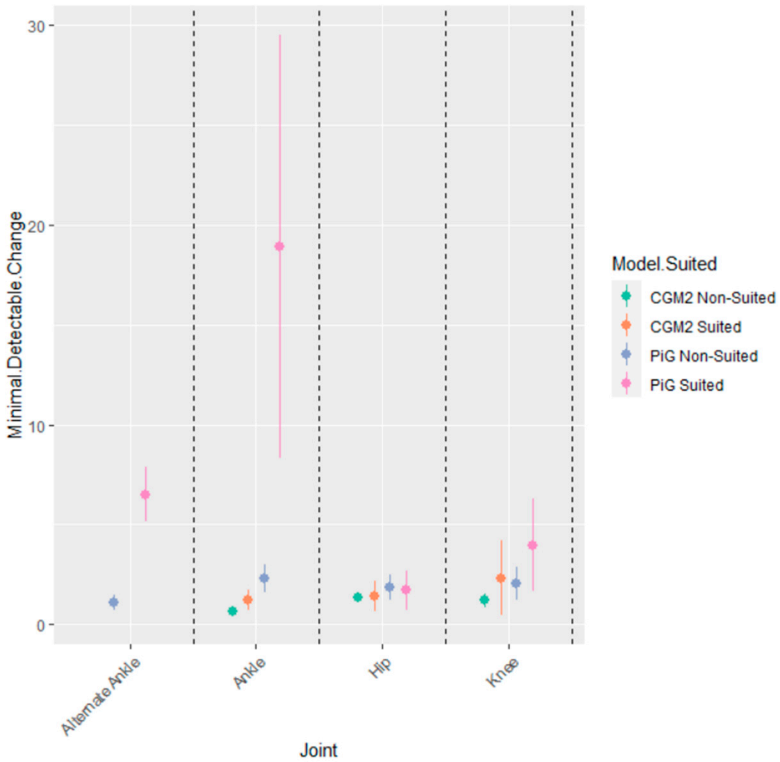



**Figure 3.** Mean and 95% CI of MDC values for each joint (PiG ankle, alternative ankle, knee, hip and CGM2 ankle, knee and hip) and for both suited and non-suited conditions.

### *3.2. Knee Angle Variables*

PiG definition: Knee angle ICC values were similar between the suited and non-suited trials, and both classed as moderate to good (Table 1). ICCs were higher in HS, Max and Min events in the non-suited trials than in the suited trials. The ICC was higher at TO in the suited trials compared to the non-suited trials, with similar variation in ICC values across all events (range: suited 0.631–0.801, non-suited 0.731–0.899). Average ICC values across events were higher in the non-suited trials (0.832) compared to the suited trials (0.707) but did not differ significantly between conditions ($p$ = 0.13) (Table 1). CGM2 definition. Compared to the PiG model, the CGM2 did not perform significantly better, with average ICCs in the non-suited trials being comparable (PiG ICC = 0.832; CGM2 ICC = 0.878; PDifference = 0.15); however, in the suited, there was a significant difference (PiG ICC = 0.707; CGM2 ICC = 0.855; PDifference = 0.01). Using the CGM2 definition, knee angle showed good to excellent reliability across all timepoints (0.829–0.910) in the non-suited trials. In the suited trials, reliability was good across all timepoints (0.769–0.895). There were no significant differences in the ICC values between the suited and non-suited trials (PDifference = 0.90) (Table 2).

PiG definition: The average MDC in the non-suited trials was 3.98°, compared to the non-suited trials, where average MDC was 2.05°, though differences were not significant ($p$ = 0.59) (Table 1). CGM2 Definition: There was no difference in the MDC when comparing the PiG and CGM2 definitions in the non-suited conditions (PDifference = 0.21). There was, however, a difference in the suited condition, with the MDC in the PiG significantly higher than the CGM2 (PDifference = 0.02) (Figure 3). When comparing the suited and non-suited condition in the CGM2 definition, there was no difference (PDifference = 0.16). However, it should be noted that the average MDC was higher in the suited condition (MDC = 2.32°) and almost double the non-suited condition (MDC = 1.20°).

### *3.3. Hip Angle Variables*

PiG definition: The hip shows the highest reliability of all three joints in both conditions, with good to excellent reliability for all metrics in both non-suited (ICC > 0.869) and suited (ICC > 0.925) conditions. The average ICC value was higher in the suited trials (0.945) compared to the non-suited trials (0.899) (but not significantly; $p$ = 0.19) (Table 1) and ICC values were higher in the suited trials across all events (but not significantly; $p$ = 0.08). CGM2 definition: There was no difference between the PiG and CGM2 definitions in the non-suited trials, with each having excellent reliability (PiG ICC = 0.899; CGM2 ICC = 0.897; PDifference = 0.83). Interestingly, there was a difference in the suited trials, even though the mean ICCs were very similar (PiG ICC = 0.945; CGM2 ICC = 0.948; PDifference = 0.02). Using CGM2, there was good to excellent reliability across all timepoints in the non-suited condition (0.879–0.912) and excellent reliability across all timepoints in the suited condition (0.941–0.965) (PDifference = 0.54).

PiG definition: The average MDC was smaller in the suited trials (1.71°) than the non-suited trials (1.88°) when looking at the hip, though not significantly ($p$ = 0.07) (Table 1). At the hip, we observed the smallest difference between conditions in the ICC and MDC. CGM2 definition: Comparing the two model definitions, there was no difference in the non-suited condition (PDifference = 0.37) or the suited condition (PDifference = 0.05). There was also no difference in the average MDC between the suited and non-suited conditions when using the CGM2 model with values across all timepoints between (0.79–1.99°; PDifference = 0.46).

### *3.4. Ankle Angle Variables (Alternative Foot Definition)*

Using the alternative foot definition, reliability improved from poor to moderate in the suited, and from moderate to good in the non-suited conditions. Average ICC values in the suited (0.648) and non-suited trials (0.826) increased compared to the standard foot definition (Figure 2). ICC values were higher across all events in the non-suited trials (range 0.754–0.937) compared to the suited trials (range 0.556–0.707), with a significant difference observed between the two conditions ($p$ < 0.001).

The ankle angle MDC in the non-suited trials was approximately 6x smaller than in the suited trials (Figure 3). The average MDC across all events in the non-suited trials was 1.11° and in the suited trials 6.51° ($p$ < 0.001). There was a twofold decrease in the MDC in the non-suited trials and an even larger decrease in the suited trials when comparing the alternative foot ($p$ = 0.02) to the standard PiG foot definition.

## 4. Discussion

### *4.1. Summary of Study Aims*

This study aimed to investigate the test–retest reliability of lower limb gait kinematics in the sagittal plane estimated based on the PiG and CGM2 marker sets from data collected with motion capture suits compared to markers placed directly onto the skin. The purpose was to provide a reference for test–retest reliability that can be used by other studies using populations for which marker attachment directly to the skin is problematic. This study also aimed to evaluate the use of an alternative foot definition to improve reliability and reduce known weaknesses of the PiG model related to reliability of ankle angles.

### *4.2. Summary of Results*

Ankle angle metric reliability was poor in the suited and moderate at best in the non-suited conditions when using the PiG model, but good to excellent in the suited trials and excellent in the non-suited trials when using the CGM2 model. Using the PiG model, reliability of knee angle metrics was moderate, and hip angle metrics good to excellent, in both suited and non-suited conditions. The CGM2 model, showed good to excellent reliability across both suited and non-suited conditions at the knee and in non-suited conditions at the hip, with the hip showing excellent reliability across all timepoints during the suited condition. The MDC of the ankle angle was significantly smaller in the non-suited condition than the suited using the PiG model. The CGM2 model showed no statistical difference between the suited and non-suited conditions with MDCs ranging from 0.46–0.76° in the non-suited and 0.91–1.49° in the suited conditions (PDifference = 0.083). There was little difference in PiG MDC of knee or hip angle metrics between non-suited and suited conditions. CGM2 showed similar trends, with little difference between the MDCs of both knee and hip angle metrics in suited and non-suited trials. The CGM2 model performed better than the PiG model with MDCs at the ankle being significantly lower in both suited ($p = 0.03$) and non-suited ($p < 0.01$) conditions and significantly lower in suited conditions at both the knee ($p = 0.03$) and hip ($p = 0.02$). An alternative foot segment definition for PiG improved reliability of the ankle angle in both conditions compared to the PiG, with good reliability in the non-suited conditions and moderate in the suited.

### *4.3. Reliability*

Comparing reliability of joint angles in both non-suited and suited conditions, we can begin to evaluate whether MOCAP suits are reliable enough to use for data collection. At the ankle and knee, reliability of the PiG non-suited trials was better (Ankle ICC = 0.531, Knee ICC = 0.832) than the suited (Ankle ICC = 0.435. Knee ICC = 0.707). Large confidence intervals (Figure 2) in the ankle and knee angle are masking potential differences between suited and non-suited conditions, as we see large differences in mean ICC values but observe no statistical difference (Ankle $p = 0.32$, Knee $p = 0.13$). These large confidence intervals, particularly at the ankle, were a result of the wide reliability range across the four metrics measured in the gait cycle. Therefore, just looking at ICC values, we cannot conclude that the MOCAP suit in conjunction with the PiG model is a viable option for research repeatedly estimating ankle and knee angles from MOCAP data. In contrast, hip angle metrics in the suited condition (ICC = 0.945) had greater reliability than in the non-suited condition (ICC = 0.899). The reliability of hip joint angles across all gait events were not significantly different between the suited and non-suited conditions, suggesting that using the MOCAP suit in conjunction with the PiG model may be a viable option for hip angle data collection.

The ICC results presented here contrast with findings from Okahisa et al. (2023) [4], who looked at the between-day reliability of the PiG model during running. They reported higher reliability in ankle angle metrics: ankle initial contact (ICC = 0.87), peak flexion (ICC = 0.68) and extension (ICC = 0.90) [4], compared to the current study. We may see differences as participants run barefoot, increasing the accuracy of marker placement on the feet, whereas in the present study markers were attached to the participant's shoes. It has previously been noted [26] that walking barefoot does change the gait characteristics and therefore measuring parameters barefoot, although this might increase marker placement accuracy, may decrease the ecological applicability of the results. While PiG knee angle metric reliability was comparable to those reported in Okahisa et al. (2023) [4], the PiG hip angle metrics were more reliable in both conditions of the present study when compared to the results of Okahisa et al. (2023) [4] (ICC at initial contact = 0.8). However, Okahisa et al. (2023) [4] assessed between-day reliability. Therefore, we cannot make direct comparison to the ICCs reported in the current study, which were taken from trials taken within one testing session.

The CGM2 model seems to be a much more reliable alternative to the PiG model when using MOCAP suits, with good to excellent reliability across all joints in both suited and non-suited conditions (ICC: 0.769–0.965). The least reliable joint was the knee with an average ICC of 0.855. The non-suited condition did not perform significantly more reliably at any of the three joints and, as a result, the use of MOCAP suits in conjunction with the CGM2 model can be recommended as an alternative to placing markers directly onto the skin to repeatedly assess ankle, knee and hip angles in the sagittal plane. These results are comparable to the reliability of the CGM2 model reported by Okahisa et al. (2023) [4], who reported sagittal ICC values of the ankle, knee and hip between 0.73 and 0.93.

The large difference in reliability when comparing the two models may be a result of the way the shank segment is defined in each model. The CGM2 model uses both lateral and medial joint markers to define the knee and ankle joint centres, with the shank orientation determined by the lateral ankle marker, a bony landmark. The PiG, however, only uses lateral markers to determine joint centres and determines the shank orientation on a tibial marker, which is placed halfway down the shank. This marker is not over a bony landmark and will therefore be hard to place consistently. We therefore may see larger discrepancies in the orientation of the shank coordinate system with PiG, which is critical given that its axes are measured in relation to the foot segment coordinate system to calculate ankle angle.

### *4.4. Minimal Detectable Change*

The MDC, used here as a measure of absolute reliability, allows us to compare the reliability of the suit across literature to evaluate it as a viable alternative to current methods. It also provides a measure of the change in the variable that would need to be seen, in order to enable a research study to conclude that changes were the result of some intervention, rather than differences in marker placement.

For ankle angle, there are significant differences in the PiG MDC with the non-suited trials (2.32°) compared to the suited trials (18.90°). The difference between the conditions, not observed in the ICC values, arises from the inclusion of the standard deviation (SD) when calculating the SEM (Equation (1)), which is in turn used to calculate the MDC (Equation (2)). We see smaller and non-significant differences between the knee (non-suited = 2.06°, suited = 3.98°) and hip (non-suited = 1.88, suited = 1.71) angles across conditions.

A systematic review of MOCAP reliability suggested that an acceptable limit of measurement error was up to 5° [1]. To this standard, all three PiG joint angles in the non-suited condition, the knee and hip angles in the suited condition and all CGM2 joint angles, both suited and non-suited, had an MDC below this 5° threshold. The PiG suited ankle MDC is almost 4× the limit, making it inappropriate for establishing changes in ankle joint angles. Arguably, when collecting clinical data, even 5° is insufficient. Studies using footwear interventions [7,8] have reported subtle changes in ankle dorsiflexion of 3.9° due to the addition of a heel lift [8]. Another prospective study [27] compared the running data of females with iliotibial band syndrome and healthy controls and found differences of 3.5° and 3.7° in peak hip adduction and knee internal rotation angles, respectively [27]. These studies [7,8,27,28] highlight the need to push reliability standards of MOCAP further to ensure detection of small changes, and further highlight that the PiG model should be used with extreme caution when in conjunction with MOCAP suits. When comparing the MDC values with Okahisa et al. (2023) [4], ankle MDC in the PiG model was reported between 3.5 and 6.8°, which is slightly larger than the average non-suited ankle MDC in the present study and comparable to the suited alternative ankle MDC, but much smaller than the suited ankle MDC (18.90°). Using PiG at the knee, Okahisa et al. (2023) [4] reported MDC angles between 4.8 and 6.4°, which is larger than the average MDCs reported in the present study in both suited (2.32°) and non-suited conditions (1.20°). In the hip, the average MDC angle reported was 7.83° [4], much larger than the Hip MDCs in both conditions reported in the present study (1.71–1.88°).

The CGM2 model provides a maximum MDC of 4.21° at the knee during HS. This is, however, an outlier, with the remaining MDC values between 0.79° and 2.62° across all joints and conditions. As a result, the CGM2 model provides improved reliability when compared to the PiG model. These MDC figures, well below the 5° acceptable limit of measurement error [1], allow us to recommend the CGM2 model as a suitable method for collecting ankle, knee and hip sagittal plane data with and without the use of a MOCAP suit. This can be compared to Okahisa et al. (2023) [4], whose average MDCs of the knee and hip across all three measurements were 5.1° at the hip and 3.2° at the knee compared to an average MDC of 1.35 at the non-suited hip and 1.45° at the suited. At the knee, the average MDC was lower again in the present study, with the average MDC at 1.20° in the non-suited and 2.32° in the suited condition.

### *4.5. Alternative Foot Definition*

The source of error resulting in PiG poor reliability of the ankle angle and the large MDC in the suit was identified as inconsistent placement of heel and toe markers. The PiG relies on careful alignment of these markers with the AJC. If toe and heel markers are not aligned with the AJC, incorrect inversion/eversion of the foot segment will ensue (Figure 4). This altered measured ankle angles by up to 80°, reducing reliability. This error was observed in both conditions, but was more common in suited trials. The alignment of the heel, AJC and toe becomes particularly difficult when using the MOCAP suit slippers which are bulky and poorly fitting, making it hard to consistently mark-up toe and heel markers.

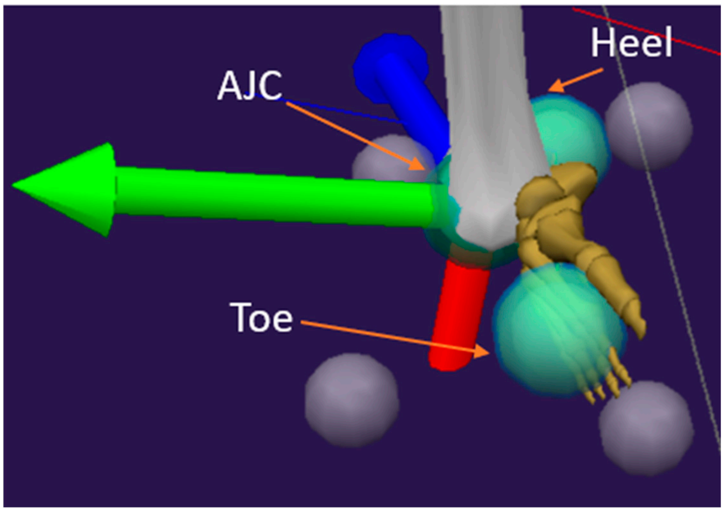



**Figure 4.** Example of rotation of the foot segment due to the incorrect placement of the heel and toe markers.

An alternative foot segment definition, which we believe has not yet been presented in other literature, in conjunction with the rest of the PiG model, improved ankle angle reliability and reduced the MDC in both conditions. This alternative foot definition presented in this paper (Figure 1b) uses easily identifiable landmarks (lateral malleolus) not affected by the suit slippers. We see reliability of the ankle angle increase from poor to moderate in the suited trials and moderate to good in the non-suited condition. There is also a large decrease in the suited MDC to 6.51°, much closer to the established maximum acceptable error, and a decrease in the ankle angle MDC in the non-suited condition (1.12°). We propose, when small changes in ankle angle are being measured, using the PiG marker set;

the alternative foot segment definition may provide a more accurate method of estimating ankle angles when compared to the typical PiG foot segment definition.

### 4.6. Markerless Motion Capture

One of the key advantages of using a MOCAP suit is the increased speed at which data collection can be conducted. Markerless motion capture, which uses regular cameras as opposed to infrared cameras, is constantly improving with the use of machine learning and may provide a faster and cost-efficient alternative to traditional motion capture, rendering MOCAP suits irrelevant. Commercial products, such as Theia3D (Theia Markerless Inc., Kingston, ON, Canada), have been the subject of studies evaluating the accuracy and reliability of markerless motion capture compared to traditional motion capture. Tishya et al. (2023) compared the kinematics measured from the PiG model using markers and the Theia3D markerless inverse kinematics model [29]. The study [29] reported that root mean square difference (RMSD) values generally differed by less than 6°. The markerless system did, however, show greater intertrial variability and was concluded to not yet be sufficiently accurate or reliable to pose as an alternative method to marker-based motion capture. In contrast, Kanko et al. (2021) [30] reported that a markerless Theia3D system gave similar values to a marker motion capture system with RMSD values lower than 5.5° for almost all segment angles, concluding that this is a viable alternative to traditional motion capture. However, this study [30] did not evaluate the test–retest reliability of either the marker or markerless system and, therefore, although these systems may be producing similar results, they may not be producing reliable results. As a result, it might be suggested that there is not yet evidence that markerless motion capture technologies match the established reliability of marker-based MOCAP techniques [29], although they present an exciting prospect for the future of minimally invasive MOCAP.

### 4.7. Limitations

We acknowledge some limitations of the present study, with kinematic reliability assessed for only a limited number of discrete metrics for sagittal plane angles during treadmill walking. The effect of a MOCAP suit on test–retest reliability in other contexts across different joint planes should be investigated in future research. It is also acknowledged that the use of only one researcher is also a limitation, and we are therefore not able to assess the effect of this researcher on reliability. The inter-tester reliability is certainly an area that should be studied in future work. However, speaking of the ecological applicability of the study, there would typically be only one researcher marking up participants during a study to ensure consistency. The use of healthy controls does limit the generalisability to clinical populations; however, due to the data collection being quite long, and the application and reapplication of markers potentially damaging to frailer skin, it was less appropriate to ask a clinical population to be tested for the sole purpose of reliability. In future, based on this protocol, intervention studies should estimate reliability and MDC based on control group data. Although MOCAP suits present a potential benefit to researchers and clinicians, they also pose potential limitations that may prevent the widespread adoption of their use. Firstly, a MOCAP suit is fairly expensive if purchased from an official MOCAP technologies company, with the suits used in this study costing up to $325 each [31]. This also means that to have variability in the body sizes of a population, it would be necessary to buy multiple suits of different sizes to ensure an adequate fit. Finally, the Velcro markers used for the suit cannot be attached to the skin and therefore are only useful for suited data collection. This, therefore, adds another cost, as another set of MOCAP markers are required if both suited and non-suited MOCAP techniques are to be used.

## 5. Conclusions

For the ankle angle metrics, the MOCAP suit results in highly unreliable measures during treadmill walking using the PiG model. The use of an alternative foot segment definition to the PiG model increases reliability and decreases MDC of the ankle angle metrics (MDC = 6.51°), but this is still above the 5-degree accepted threshold. Therefore, when using PiG, placing makers on suits at the ankle and foot is not a viable alternative to applying markers directly to the skin or shoe. The MOCAP suit has some merit when looking at the knee and hip angles, with reliability and MDC similar to attaching markers directly to the skin. However, the CGM2 model performs far better than the PiG model in both suited and non-suited conditions at the ankle, and better in suited conditions at the knee and hip. The CGM2 model shows good to excellent reliability in the suited trials at the ankle and knee, in the non-suited trials at the knee and hip, excellent reliability in the suited trials at the hip and in the non-suited trials at the ankle. The MDCs across all joints in both suited and non-suited conditions are well below the 5° accepted threshold and, therefore, it is recommended that the MOCAP suit can be used for more efficient MOCAP data collection in conjunction with the CGM2 model but not with the PiG model.

**Author Contributions:** Conceptualization, M.C.S., P.L. and G.K.R.W.; methodology, M.C.S. and G.K.R.W.; software, M.C.S., P.L. and G.M.; validation, M.C.S., G.M. and G.K.R.W.; formal analysis, M.C.S.; investigation, M.C.S. and G.K.R.W.; resources, J.T., G.K.R.W. and M.H.; data curation, M.C.S.; writing—original draft preparation, M.C.S., P.L. and G.K.R.W.; writing—review and editing, J.T., M.H. and G.K.R.W.; visualization, M.C.S. and P.L.; supervision, G.K.R.W., J.T. and M.H.; project administration, J.T., G.K.R.W. and M.H.; funding acquisition, J.T., G.K.R.W. and M.H. All authors have read and agreed to the published version of the manuscript.

**Funding:** (1) M.C.S. was supported by The Graham Cole Ph.D. Studentship; (2) This study is funded by the National Institute for Health and Care Research (NIHR) Exeter Biomedical Research Centre (BRC). The views expressed are those of the author(s) and not necessarily those of the NIHR or the Department of Health and Social Care.

**Institutional Review Board Statement:** The study was conducted in accordance with the Declaration of Helsinki and approved by the research ethics committee of The University of Exeter for studies involving humans (Approval number: 1212092; Date: 3 April 2023).

**Informed Consent Statement:** Informed consent was obtained from all subjects involved in the study.

**Data Availability Statement:** The raw data supporting the conclusions of this article will be made available by the authors on request.

**Conflicts of Interest:** The authors declare no conflicts of interest. The funding sources had no such involvement in study design; in the collection, analysis and interpretation of data; in the writing of the report; and in the decision to submit the article for publication.

## References


1. McGinley, J.L.; Baker, R.; Wolfe, R.; Morris, M.E. The reliability of three-dimensional kinematic gait measurements: A systematic review. *Gait Posture* **2009**, *29*, 360–369. [CrossRef] [PubMed]
2. Molina-Rueda, F.; Fernández-González, P.; Cuesta-Gómez, A.; Koutsou, A.; Carratalá-Tejada, M.; Miangolarra-Page, J.C. Test-Retest Reliability of a Conventional Gait Model for Registering Joint Angles during Initial Contact and Toe-Off in Healthy Subjects. *Int. J. Environ. Res. Public Health* **2021**, *18*, 1343. [CrossRef] [PubMed]
3. Leboeuf, F.; Baker, R.; Barré, A.; Reay, J.; Jones, R.; Sangeux, M. The conventional gait model, an open-source implementation that reproduces the past but prepares for the future. *Gait Posture* **2019**, *69*, 235–241. [CrossRef] [PubMed]
4. Okahisa, T.; Matsuura, T.; Tomonari, K.; Komatsu, K.; Yokoyama, K.; Iwase, J.; Yamada, M.; Sairyo, K. Between-day reliability and minimum detectable change of the Conventional Gait Model 2 and Plug-in Gait Model during running. *Gait Posture* **2023**, *100*, 171–178. [CrossRef]
5. Collier, M. Minimising pain and medical adhesive related skin injuries in vulnerable patients. *Br. J. Nurs.* **2019**, *28*, S26–S32. [CrossRef]
6. Yavuzer, G.; Öken, Ö.; Elhan, A.; Stam, H.J. Stam Repeatability of lower limb three-dimensional kinematics in patients with stroke. *Gait Posture* **2008**, *27*, 31–35. [CrossRef]
7. Hutchison, L.; Scharfbillig, R.; Uden, H.; Bishop, C. The effect of footwear and foot orthoses on transverse plane knee motion during running—A pilot study. *J. Sci. Med. Sport* **2015**, *18*, 748–752. [CrossRef]
8. Dixon, S.J.; Kerwin, D.G. The Influence of Heal Lift Manipulation on Sagittal Plane Kinematics in Running. *J. Appl. Biomech.* **1999**, *15*, 139–151. [CrossRef]

9. Damiano, D.L.; Arnold, A.S.; Steele, K.M.; Delp, S.L. Can Strength Training Predictably Improve Gait Kinematics? A Pilot Study on the Effects of Hip and Knee Extensor Strengthening on Lower-Extremity Alignment in Cerebral Palsy. *Phys. Ther. Rehabil. J.* **2010**, *90*, 269–279. [CrossRef]
10. Hedrick, E.A.; Malcolm, P.; Wilken, J.M.; Takahashi, K.Z. The effects of ankle stiffness on mechanics and energetics of walking with added loads: A prosthetic emulator study. *J. NeuroEngineering Rehabil.* **2019**, *16*, 148. [CrossRef]
11. Boyer, K.A.; Johnson, R.T.; Banks, J.J.; Jewell, C.; Hafer, J.F. Systematic review and meta-analysis of gait mechanics in young and older adults. *Exp. Gerontol.* **2017**, *95*, 63–70. [CrossRef] [PubMed]
12. *Motek R Mill M-Gait*; Motek Medical: Houten, The Netherlands, 2023.
13. Vicon. About the Conventional Gait Model 2.3. Available online: https://help.vicon.com/download/attachments/12651006/Vicon%20ProCalc%20Generating%20VSKs%20Tutorial.pdf (accessed on 21 September 2024).
14. *Qualisys Qualisys Track Manager*; Qualisys: Gothenburg, Sweden, 2021.
15. C-Motion. *Visual 3D*; C-Motion: Rockville, MD, USA, 2024.
16. Tutorial: Plug-In Gait Lower-Limb. Available online: https://www.c-motion.com/v3dwiki/index.php?title=Tutorial:_Plug-In_Gait_Lower-Limb (accessed on 15 September 2024).
17. Vicon. *Vicon Procalc Generating Vsks Tutorial*; Vicon: Hauppauge, NY, USA, 2021.
18. Zeni, J.A.; Richards, J.G.; Higginson, J. Two simple methods for determining gait events during treadmill and overground walking using kinematic data. *Gait Posture* **2008**, *27*, 710–714. [CrossRef] [PubMed]
19. Wu, G.; Siegler, S.; Allard, P.; Kirtley, C.; Leardini, A.; Rosenbaum, D.; Whittle, M.; DD'Lima, D.; Cristofolini, L.; Witte, H.; et al. ISB recommendation on definitions of joint coordinate system of various joint motion—Part I: Ankle, hip, and spine. *J. Biomech.* **2002**, *35*, 543–548. [CrossRef]
20. Landers, R.N. Computing intraclass correlations (ICC) as estimates of interrater reliability in SPSS. *Authorea* **2015**. [CrossRef]
21. Koo, T.K.; Li, M.Y. A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. *J. Chiropr. Med.* **2016**, *15*, 155–163. [CrossRef]
22. Furlan, L.; Sterr, A. The applicability of standard error of measurement and minimal detectable change to motor learning research—A behavioral study. *Front. Hum. Neurosci.* **2018**, *12*, 95. [CrossRef]
23. IBM Corp. *SPSS Statistics for Windows*; IBM: Armonk, NY, USA, 2021.
24. Villalba, F.J.; Policastro, P.O.; Soliño, S.; Andreu, M.; Novoa, G.A.; Raguzzi, I.A.; Pierobon, A. Standard measurement error and minimal detectable change of the Back-PAQ ArgSpan questionnaire: Secondary analysis. *Musculoskelet. Sci. Pract.* **2021**, *51*, 102315. [CrossRef]
25. Amanda Ross, V.L.W. Paired Samples T-Test. In *Basic and Advanced Statistical Tests*; Springer: Berlin/Heidelberg, Germany, 2017; pp. 17–19.
26. Franklin, S.; Grey, M.J.; Heneghan, N.; Bowen, L.; Li, F.X. Barefoot vs common footwear: A systematic review of the kinematic, kinetic and muscle activity differences during walking. *Gait Posture* **2015**, *42*, 230–239. [CrossRef] [PubMed]
27. Noehren, B.; Davis, I.; Hamill, J. ASB Clinical Biomechanics Award Winner 2006: Prospective study of the biomechanical factors associated with iliotibial band syndrome. *Clin. Biomech.* **2007**, *22*, 951–956. [CrossRef]
28. Devetak, G.F.; Martello, S.K.; de Almeida, J.C.; Correa, K.P.; Iucksch, D.D.; Manffra, E.F. Reliability and minimum detectable change of the gait profile score for post-stroke patients. *Gait Posture* **2016**, *49*, 382–387. [CrossRef]
29. Tishya, A.L.; Wren, P.I.; Susan, A. Rethlefsen Comparison of kinematics between Theia markerless and conventional marker-based gait analysis in clinical patients. *Gait Posture* **2023**, *104*, 9–14.
30. Robert, M.; Kanko, E.K.L.; Elysia, M.; Davis, W.; Scott Selbie Kevin, J. Deluzio Comparison of kinematics between Theia markerless and conventional marker-based gait analysis in clinical patients. *J. Biomech.* **2021**, *127*.
31. Optitrack.com. Available online: https://optitrack.com/accessories/wear/ (accessed on 15 September 2024).