## INTRODUCTION

Various health conditions, for example cerebral palsy [1], clubfoot [2] and hereditary motor and sensory neuropathy [3], may impair foot function. Using kinematic modelling to measure foot kinematics during walking can aid clinical decision making [4]. Whilst traditionally the foot was modelled as a single rigid segment [5], this approach does not reflect underlying foot biomechanics [6,7]. However, recent advances in multi-segment foot modelling [8,9] now allow the foot to be modelled as individual foot segments.

Numerous skin mounted multi-segment foot models exist, with considerable variation in segment definition, modelling, repeatability and equipment, resulting in a complex array of models [8,9] suited to different clinical and biomechanical situations [10]. The Oxford Foot Model (OFM) [11,12] is a six degrees of freedom foot model comprising three true segments (tibia, hindfoot [calcaneus], and forefoot [five metatarsals]) whilst the hallux is modelled as a vector. The OFM is considered the most widely applied model in the clinical setting [8,9] and has been involved in at least 22 clinical research studies [10], many focussing on foot pathology (for example [13,14]).

Kinematic models that rely on skin mounted markers to define and track segments are particularly sensitive to measurement variability. Precise identification of specific anatomical landmarks that guide skin marker placement can be difficult [5], resulting in measurement errors. A thorough understanding of kinematic measurement errors, acquired through repeatability studies, is essential to avoid over or under interpretation of clinical data. It is important to understand whether differences in repeated measurements are likely attributable to measurement error or true change in the patient [15]. OFM repeatability during barefoot walking has been measured in healthy children [12,16,17,18], healthy adults [11,19,20] and children with underlying foot deformities [18]. Of these studies, three [11,12,18] have been conducted by the originators and implementers of the model, whilst one study [16] is co-authored with the originators. Most studies independent of the originators have examined intra-assessor agreement (measurements repeated by the same assessor) [17,20] while one [19] focussed on inter-assessor agreement (measurements repeated by more than one assessor) related to two assessors. As these publications do not describe assessor experience, it is difficult to establish the clinical utility of the OFM when applied by gait analysts with varied backgrounds who learn about the model only from published resources alone. Caravaggi et al. [21] concluded from their study of the Rizzoli foot model that errors were lower when measurements were made by experienced assessors, however, no such conclusions can be made in relation to the OFM. Generally, as discussed by McGinley et al [24], assessor characteristics are often poorly documented in marker placement repeatability studies, limiting conclusions on the relationship between assessor experience and error.

No studies have measured OFM repeatability between more than two assessors, however, large gait laboratories may rely on several clinicians to collect data from different patients and repeat analyses on the same patient. Therefore, it is essential that marker placement errors are fully understood when interpreting patient data. As such, the primary aim of this study is to establish the quality of results expected from the OFM after a short training period by measuring the intra- and inter-assessor repeatability of the OFM throughout the gait cycle during self-selected walking in healthy adults when applied by three assessors with different professional backgrounds and varied lower limb marker placement experience. Assessors will have no prior practical experience of the model but will receive a training package developed from published resources alone. We assume measurements made by assessors with significant general lower limb marker placement experience will be associated with less errors, however there will be good agreement between assessors (inter-assessor error below $5^{0}$ for all joint angles). Additionally, we aim to present this article in such a way that the methodology and statistical analysis are clear enough to allow replication or a direct comparison with future studies. Not all previous published studies provide a specific, consistent and repeatable explanation of data analysis, all appearing to have employed slightly different statistical analyses focussing on different timepoints in the gait cycle, preventing direct comparison with other studies.

## METHOD

### *Overview*

Following ethical approval, a repeated measures design was employed whereby three assessors each collected three sets of data from ten participants (6 female, average age 31.1 years [± 8.3], height 171.8cm [±7.8], mass 69.3kg [±10.1]) recruited voluntarily from a University population, totalling ninety sessions. The sample size was chosen to replicate previous studies [16,19]. Exclusion criteria were current/previous unresolved pain or neuromusculoskeletal pathology; severe skin conditions; pregnancy/breast feeding and a BMI over 30. Assessors had varied experience of lower limb marker application in general, but no practical experience of the OFM and were chosen to provide an insight into its clinical utility.

At the time of the study Assessor One (Physiotherapist and Lecturer) had three years of independent lower limb marker placement experience and had worked as a physiotherapist for 17 years, particularly focussing on musculoskeletal and paediatric pathologies of the lower limb. Assessor Two was a graduate Mechanical Engineer training to become a Clinical Scientist. Whilst Assessor Two had some experience of supervised general lower limb marker placement (five sessions) and a practical understanding of lower limb modelling, at the time of the study they had not received formal exposure, through their Masters degree curriculum, to the theory underpinning biomechanical modelling or marker placement. Assessor Two had not been exposed to formal teaching and learning on lower limb anatomy. Assessor Three was a graduate Kinesiologist and immediately after graduation embarked on a Master's degree in Biomedical Kinesiology. Assessor Three had no theoretical or practical gait laboratory or lower limb marker placement experience but had previously received a two hour lecture explaining the background of the Conventional Gait Model. However, Assessor Three had a clear understanding of anatomy having received 200 hours of undergraduate functional anatomy training and 75 hours of training on palpation (with approximately one third of this time devoted to the lower limb). Two colleagues (Engineer/Engineer and Professor of Clinical Gait Analysis) devised a marker placement protocol using published resources including Vicon guidelines (Vicon Motion Systems, Oxford, UK) and books/papers [5,11,12]. Assessor One provided input to the protocol using their previous knowledge of how to locate and palpate bony landmarks, supported by material that was already known to Assessor One [22]. Assessor One was the only assessor to have previous general theoretical knowledge of the OFM, having been exposed to books and articles that provided an overview. No assessors had practical experience of the OFM. The protocol was provided to each assessor two weeks before the start of the study and formed the basis of two 90 minute group learning sessions facilitated by the Engineer (one theoretical and one practical). The group learning sessions were tailored to meet all needs and began by outlining bony anatomy of the leg and foot using bone models. Sessions then moved on to clearly outline how to identify and palpate the bony landmarks associated with OFM marker placement (according to Van Sint Jan [22]). Finally, sessions guided assessors on how to align marker baseplates precisely to each landmark and the impact of mal-alignment on the model. Pen marks were used to guide marker placement.

***Data collection***

Following informed consent, each participant attended on three separate occasions, spaced one to two weeks apart to prevent marker placement recall. Vicon Nexus 2 software and ten T-40 infra-red cameras (Vicon, Oxford metrics, Oxford, UK) captured marker 3D trajectories following system calibration according to manufacturer's guidelines with four force plates (Kistler, Alton, UK) used to detect gait events.

Each assessor applied the OFM to the right leg according to the model variation 5 (omitting the heel wand) as defined in Stebbins et al. [12]. Assessors were permitted to refer to the protocol during marker placement. Following acquisition of a static trial (relaxed standing, 'foot flat') and practice walks, participants were asked to walk at self-selected speeds (10m walkway) and marker trajectories were captured at 100Hz for a minimum of 10 trials. This procedure was repeated by the other assessors on the same day and then repeated by all assessors twice more (with a gap of one to two weeks). Assessors were blind to marker placement by other assessors and alcohol wipes were used to redden the skin if any marks were evident from previous applications.

***Data processing***

For each session between four and six walking trials (mean 5.9) from the right leg with clean force plate contacts and no marker loss were analysed. Following detection of gait events using force plates, data were labelled then filtered using a spline smoothing technique [26]. The OFM was applied using Bodybuilder code (Vicon, Oxford metrics, Oxford, UK) which defined the tibia segment according to Stebbins et al. [12]. All data were time normalised for statistical analysis.

***Statistical processing***

The standard error of measurement (SEM – within-participant standard deviation) was chosen because it is an absolute measure of error (documented in the unit of measurement). Therefore it is more clinically meaningful than reliability indices [5] and it relates to published articles in this field. In addition to the SEM, a 95% upper confidence limit was calculated for each joint angle according to the procedure outlined in table 1. Inter-trial variability was also calculated according to Schwartz et al. (2004) [28].

(Table 1)

All data and calculations from this study are presented in Appendix 1.

## RESULTS

***Walking speed***

Average walking speed (mean +/- 1SD across 90 data collection sessions) was 1.3±0.2 m.s-1. Average variation in walking speed for a single participant was 4.0±1.6% (calculated with one standard deviation from the participant's mean walking speed over nine sessions, presented as a percentage).

***Inter-trial variability***

The variation in how participants walked during their four to six trials per session (inter-trial variability) ranged from 0.6-1.4°. The difference in inter-trial variability was never more than 0.2° between assessors at the same joint angle.

***Inter-assessor error***

(Figure 1)

Figure 1a presents SEM values whilst figure 1b displays SEM plus the 95% upper confidence limit. Figure 1b shows that inter-assessor errors fell between 2.2° (forefoot/hindfoot dorsiflexion) and 5.5° (hindfoot/tibia internal rotation). The lowest inter-assessor error occurred in the sagittal plane and the highest error was seen in the transverse plane.

***Intra-assessor error***

Intra-assessor error (figure 1b) ranged from 1.8° (assessor one forefoot/hindfoot dorsiflexion) to 5.5° (assessor two hindfoot/tibia internal rotation, forefoot/hindfoot adduction). The minimum error difference between assessors over one joint angle was 0.4° (hindfoot/tibia dorsiflexion) whilst the maximum was 1.5° (hindfoot/tibia inversion). Apart from hindfoot/tibia dorsiflexion, Assessor One demonstrated the lowest intra-assessor error and on average (across six joint angles) intra-assessor error for assessors one to three was 3.5°, 4.4° and 4.0° respectively. The lowest intra-assessor errors were associated with the sagittal plane.

***Intra-assessor vs inter-assessor error***

Intra-assessor error associated with Assessor One was always equal to or below the inter-assessor error for the same joint angle. However, the intra-assessor error for Assessor Two was more frequently higher than the inter-assessor error. Assessor Three's error tended to fall below the inter-assessor error.

***Normative data and percentage of error to range of motion***

Figure 2 displays the normative data taken from the mean +/- 1SD from 533 trials. Figure 3 plots the percentage of error (SEM + 95% confidence limit) to the mean range of motion for each angle. This varied considerably depending on the joint angle and was lowest (11%) for hindfoot/tibia dorsiflexion and highest (126%) for forefoot/hindfoot adduction.

Figure 2

Figure 3

***Study data***

All data and calculations from this study are presented in Appendix 1.

## DISCUSSION / SIGNIFICANCE

This study measured OFM repeatability across three assessors with different professional backgrounds (physiotherapy, engineering and kinesiology) and varied experience of general lower limb marker application. Assessor One had general previous theoretical exposure to the OFM but no specific modelling understanding or practical application whilst Assessors Two and three had no prior OFM experience. Assessors were not native to the laboratory where the OFM originated, however a detailed protocol and training package were provided.

***Experience versus inter-assessor error***

The inter-assessor error measures the difference between the way that Assessors One, Two and Three placed markers on the same participant during each participant visit. Maximum inter-assessor errors (plus confidence limit) were 5.5° (hindfoot/tibia internal rotation) and 5.3° (forefoot/hindfoot adduction) with all other values falling below 5°, partially confirming the hypothesis that inter-assessor error would fall below 5° for all angles. The upper limit of 5° was chosen based on the work of McGinley at al. [24], who suggest that lower limb marker placement errors between 2° and 5° are reasonable. Based on this concept, the OFM is a repeatable tool, even when applied by assessors with little or no marker placement experience and from varied backgrounds, learning about the model from published sources alone. However, the question of whether the 5° error threshold is acceptable at the foot needs to be discussed further.

### ***Experience versus intra-assessor error***

Intra-assessor error measured the difference between the way that the same assessor applied markers during repeat visits of the same participant. The difference in this error between assessors over the same joint angle varied from $0.4^{o}$ to $1.5^{o}$, confirming that each assessor performed quite similarly when asked to re-apply markers to the same participant. Assessor One (who had the most general marker placement experience) displayed the lowest intra-assessor error overall, followed by Assessor Three (no general marker placement experience) then Assessor Two (limited general marker placement experience). This confirms the hypothesis that significant marker placement experience is associated with lower errors, even when a model is new to an assessor. However, limited marker placement experience seems to have little effect on errors, and perhaps prior anatomical understanding (such as that acquired by Assessor Three, a kinesiologist) has a greater influence on reducing marker placement error. Assessor One also had a superficial theoretical understanding of the OFM and this may have contributed to lower marker placement error. Our findings agree with Caravaggi et al. [21] who concluded that assessor experience influenced the repeatability of the Rizzoli foot model, however the variation in our study is smaller.

### ***Intra-assessor vs inter-assessor error***

The intra-assessor error of Assessor One (more experience) is always equal to or below the inter-assessor error, meaning that it is more reliable for Assessor One to make repeat measurements on the same participant than share repeat sessions out between all assessors (figure 1b). This follows the recognised pattern in repeatability studies, in that intra-assessor error is usually lower than inter-assessor error as the same assessor tends to adopt their own strategy for marker placement [5], being more reliable in repeat marker placement on the same participant than relying on a team approach. However, this observation does not apply to all results for Assessors Two and Three. Intra-assessor error (figure 1b) is higher than inter-assessor error 83% of the time for Assessor Two and 33% of the time for Assessor Three.

***Clinical significance and percentage of error to range of motion***

Our study shows that, in relation to healthy adults, assessors with a background in human movement and anatomy, and those with significant general lower limb marker placement experience, may have lower errors when applying the OFM across repeated measurements on the same participant (intra-assessor errors). However generally there was little difference (maximum of 1.5°) between assessors who have received training and Assessor Two (engineering background) with little marker placement experience, was generally classed as making repeatable measurements. The model of training produced generally acceptable results for all assessors but it is unclear whether a longer training programme could have led to lower errors. In clinical practice, training packages may need to be tailored according to experience.

Based on this study, when different members of a team apply OFM markers to the same participant across different visits the errors will depend on the constitution of the team. This statement is based on healthy adult data and it is unclear how this applies to children or individuals with underlying pathology where foot size and deviations in foot anatomy and morphology come into play. It is difficult to ascertain from this study the effect of the training package on degree of error, however, it is recommended that clinical gait laboratories use clear protocols which outline standardised operating procedures [10]. It is also imperative that clinical gait analysis services conduct repeatability studies specific to their service [5] allowing local joint angle errors to be considered during clinical data interpretation. Leardini et al. [10] suggest that any changes in a patient's kinematics should be much larger than the error associated with the measure.

Based on the recommendations of McGinley et al. [24], who suggest that errors between 2° and 5° are reasonable, our study shows that the OFM is largely a repeatable multi-segment foot model (18/24 SEM measurements fell within this threshold). However, these recommendations are based on movements of the lower limb, many of which have large excursions. Conversely, the small segments of the foot give rise to smaller movements, especially in the coronal and transverse planes, where the percentage of error to total range of motion is higher. The amount of inter-assessor error (figure 3) ranges from 11.1 to 126.2% of the total (mean) range of motion. Furthermore, 4 out of 6 different joint angle error measurements equate to more than 50% of their total range of motion. Whilst the percentage of error to mean joint range of motion for hindfoot/tibia dorsiflexion (11.1%) and forefoot/hindfoot dorsiflexion (13.5%) may appear to be acceptable, the percentage is much greater for the remaining joint angles (52.4% to 126.2%). All of these values are concerning, however, forefoot/hindfoot adduction is particularly alarming at 126.2%. Thus, OFM data needs to be interpreted with a level of caution, particularly in the coronal and transverse planes, as atypical patient data may be attributable to marker placement error, rather than true atypical joint movements. The strive for accurately defining foot segments must continue in a drive to reduce the percentage of error to mean range of motion.

***Comparison to other OFM repeatability studies***

It is difficult to perform a direct comparison with published OFM repeatability studies [11,12,16,17,18,19,20] because there is much methodological variation, particularly in relation to the number and description of assessors; assessor experience; participant characteristics; number and timing of repeat walking trials and sessions; type of study; time point in the gait cycle chosen for analysis; and type of statistical analysis employed. In addition, not all studies relate to adults. However, the results from our study generally compare well with other studies as shown in figure 2 and table 2. Lower errors occur in the sagittal plane, as supported by the majority of OFM repeatability studies [11,12,16,18,19], whilst higher errors are seen in the transverse plane, in agreement with various studies [11,12,16,18]. Whilst our study has not examined the effect of specific marker mal-alignment on individual joint angles, it is likely that higher errors observed in the coronal and transverse planes are attributable to medial and lateral misplacement of the heel markers, as described by Carty et al. [25].

(Table 2)

***Limitations and future considerations***

The main limitation of this study is the sample of healthy adults. The study should be repeated in other populations as assessor error may be higher when the OFM is applied to smaller feet or those with underlying deformity. Additionally, this study only defined the tibia using the OFM and the results may be different when the tibia is defined using other biomechanical models such as Plug in Gait [27]. Due to the large array of multi-segment foot models, with at least 39 models described in the literature [10], it is beyond the scope of this paper to compare the findings to other models.

## CONCLUSION

In conclusion, our study demonstrates that the OFM is largely repeatable when measuring walking in healthy adults, applied by three assessors not native to the centre in which the model was developed, with no prior experience of the model, varied marker placement experience and different professional backgrounds. In our study, assessors with prior anatomical knowledge and more lower limb marker placement experience displayed lower errors.

The proportion of error to joint range of motion is more than half the total range of motion for some angles and is highest for forefoot/hindfoot adduction where the error exceeds the total range of movement. As such, forefoot/hindfoot adduction cannot be recommended as an outcome measure. Inter- and intra-assessor errors, specific to each laboratory, should be considered, along with the proportion of error to joint angle range when interpreting patient data.

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