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Reliability testing of the heel marker in three-dimensional gait analysis

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ABSTRACT

Introduction: In three-dimensional gait analysis, anatomical axes are defined by and therefore sensitive to marker placement. Previous analysis of the Oxford Foot Model (OFM) has suggested that the axes of the hindfoot are most sensitive to marker placement on the posterior aspect of the heel. Since other multi-segment foot models also use a similar marker, it is important to find methods to place this as accurately as possible.
The aim of this pilot study was to test two different 'jigs' (anatomical alignment devices) against eyeball marker placement to improve reliability of heel marker placement and calculation of hindfoot angles using the OFM.
Methods: Two jigs were designed using three-dimensional printing: a ratio caliper and heel mould. OFM kinematics were collected for ten healthy adults; intra-tester and inter-tester repeatability of hindfoot marker placement were assessed using both an experienced and inexperienced gait analyst for 5 clinically relevant variables.
Results: For 3 out of 5 variables the intra-tester and inter-tester variability was below 2 degrees for all methods of marker placement. The ratio caliper had the lowest intra-tester variability for the experienced gait analyst in all 5 variables and for the inexperienced gait analyst in 4 out of 5 variables. However for inter-tester variability, the ratio caliper was only lower than the eyeball method in 2 out of the 5 variables. The mould produced the worst results for 3 of the 5 variables, and was particularly prone to variability when assessing average hindfoot rotation, making it the least reliable method overall.
Conclusions: The use of the ratio caliper may improve intra-tester variability, but does not seem superior to the eyeball method of marker placement for inter-tester variability. The use of a heel mould is discouraged.

1. Introduction

In three-dimensional gait analysis, anatomical axes are defined by and therefore sensitive to marker placement [1]. In most kinematic multi-segment foot models, the posterior heel marker is used to help define the hindfoot segment by placing the marker centrally on the posterior aspect of the calcaneus. For the Oxford Foot Model (OFM) hindfoot segment, the heel (HEE), proximal heel (PCA), lateral calcaneus (LCA) and sustentaculum tali (STL) markers are used to define the axes of the calcaneus [2].

Previous research has shown that misplacement of the calcaneal markers has a profound effect on the kinematic output [3–5]. Paik and colleagues used radiopaque monitoring electrodes placed on the feet at the locations specified by the OFM and CT images to investigate how changes in marker placement affect the orientation of the OFM hindfoot segment axes [5]. Their results suggest changing the anterio-posterior position of either the LCA or the STL marker by 1 mm induced 0.2° of change in the anterior-posterior (A–P) axis. Whereas, when the HEE marker position was moved in mediolateral direction by 1 mm, it induced 4° of change in the orientation of the A–P axis [5]. Since the orientation of the A–P axis is more sensitive to the location of the HEE marker than to the locations of the LCA and STL markers, it is essential to ensure that the HEE marker is placed accurately.

Intra-tester and inter-tester repeatability of hindfoot marker placement has been shown to be improved when using an alignment device or jig to assist in marker placement, compared to using a manual

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palpation/ eyeball method; however both jigs were designed to align the medial and lateral calcaneal markers, and not the central heel marker [4, 6].

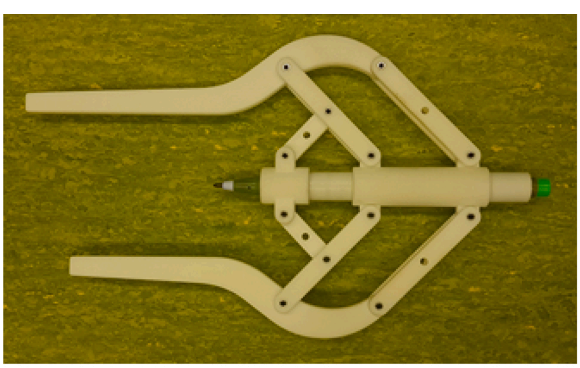
After reviewing the available alignment devices in the literature, and using the authors' expert experience with foot anatomy and the OFM, we designed two jigs that could potentially improve the repeatability of HEE marker placement: a ratio caliper and mould. The aim of this pilot study was to test these two jigs against the conventional method of eyeball marker placement to improve marker placement repeatability of the HEE marker when using the OFM. We hypothesized that the ratio caliper and mould would not improve an experienced gait analyst's repeatability (as experience generally improves repeatability), but that they would improve an inexperienced gait analyst's repeatability as well as the inter-tester error.

2. Methods

2.1. Specifications of two jigs

Two jigs were constructed using three-dimensional printing to specifications designed by the authors.

a) Ratio caliper: The longer fixed arm was placed on the lateral border of the foot to the base of the 5th metatarsal- while the shorter moving arm was brought in to the medial hindfoot. A mid-point at 50 % between the 2 arms determined the midline of the calcaneus where the HEE marker was placed. The caliper was used with the subject in weight bearing. (Picture 1a).
b) Heel mould: The foot shape for the mould was determined by a 3D light scan of the skin surface of a female with asymptomatic feet and an EU shoe size of 36. The mould was scaled to three different sizes to accommodate different shoe size ranges (small, medium, large) and 3D printed. The mould had a central hole in the middle of the calcaneus to mark with pen so the heel marker could be placed over the mark upon removal of the mould. It also had holes for the LCA and STL markers to be placed over as well. The mould was placed on the foot with the subject in a seated position (Picture 1b).



Picture 1. a) ratio caliper b) heel mould.

2.2. Definition of eyeball method

Heel marker placement for the OFM uses an eyeball technique with manual palpation to place the heel marker in the middle of the calcaneus at the same height above the plantar surface of the foot as the TOE marker (between the heads of the 2nd and 3rd metatarsals).

2.3. Repeatability testing

Ten healthy adult subjects (6 female, age: 26.8 (SD 2.6) years, height: 176.4 (8.1), weight: 67.2 (8.5) with a normal foot posture index (2.4 (1.4)) were recruited for this study [7]. The subjects did not have any foot or ankle complaints, did not wear insoles, and did not have any concerns that would affect their gait pattern. Informed consent was obtained for all subjects and ethical approval was provided by the local ethics committee. All subjects were assessed during level walking at self-selected velocity using a 12 camera motion capture system (Vicon Motion Systems Ltd., Oxford, UK) (sampling at 100 Hz) and 9.5 mm passive markers with 9.5 mm diameter bases were placed by two different gait analysts for OFM kinematics: an experienced analyst (over 10 years) and an inexperienced analyst (less than 6 months) experience with the OFM.

Each subject attended the gait laboratory for one visit. The experienced gait analyst put all the lower limb and OFM markers on initially using the eyeball method. All markers except for the calcaneal (hindfoot) markers stayed in place for the rest of the session. In order to not bias the placement of the HEE marker, all of the calcaneal markers were replaced each session, any marks on the foot were removed between trials, and the gait analysts were blinded to the other's marker placement. The HEE, CPG, PCA, STL, LCA markers [2] were replaced for the additional walking trials so both gait analysts used the eyeball, the ratio caliper, and the mould methods of marker placement for two walking sessions each (12 sessions for each subject in total). Within each session, five walking trials were recorded, and three walks (three strides) were averaged for data analysis.

All data were processed by the same person with the OFM pipeline implemented in Vicon Nexus (v2.9.3), in which the hindfoot flat option was not checked. The data were analysed using five clinically relevant variables of hindfoot motion during the gait cycle: maximum hindfoot dorsiflexion in stance, maximum hindfoot dorsiflexion in swing, range of hindfoot motion in the sagittal plane, average hindfoot varus, and average hindfoot rotation. Inter-tester repeatability was taken from the first marker application for both the gait analysts. Initially, statistical parametric mapping was used to demonstrate an absence of significant order effects within raters and an absence of a systematic difference between testers, evaluated over the full gait cycle. Subsequent analysis was applied to each of the five derived variables, in combination with each of the three methods of marker placement. A series of Bland-Altman plots were produced, one for each tester and for between the first of the tester assessments, none of which showed that differences varied with the magnitude of the observations. The standard deviations (SDs) for within tester differences and between tester differences were calculated from the root mean square of the differences We also report variance components for each intra-tester component and inter-tester component for all combinations of variable and marker method, as suggested by Chia and Sangeux [8] using restricted maximum likelihood. A pooled estimate of the intra- and inter-tester components for each of the three marker methods was obtained using the mean of the five separate estimates.

3. Results

The SDs from the intra- and inter-tester differences are shown in

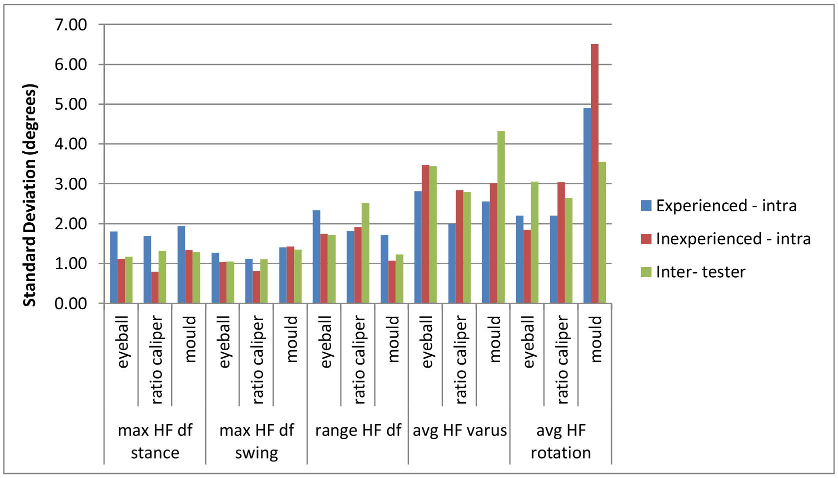


Fig. 1. Standard deviations (N = 10) in degrees of both intra-tester (experienced and inexperienced gait analysts) and inter-tester differences max = maximum, HF = hindfoot, df = dorsiflexion, avg = average.

Fig. 1. These show similar, low intra-tester differences for both gait analysts and inter-tester differences in the sagittal plane variables for all three methods of marker placement with the majority of differences under 2.0 degrees, and all differences under 2.5 degrees.

Compared to the eyeball method, the ratio caliper and the mould reduced intra-tester variability for both gait analysts for average hindfoot varus. However the mould had the highest inter-tester variability in the coronal plane compared to the other clinical variables. Average hindfoot rotation showed the highest intra-tester variability for both gait analysts, and the second highest inter-tester variability when using the mould compared to the other two methods. These findings were reinforced by the variance components, shown in Supplementary Material: Table 1. For five of the 15 combinations of variable and method, the estimate of the inter-rater component was zero.

Table 1
Variance component estimates by variable and marker placement method max = maximum, HF = hindfoot, df = dorsiflexion, avg = average.

Variable	Method	Intra-experienced (degrees)	Intra-inexperienced (degrees)	Inter-tester (degrees)
Max HF df stance	Eyeball	1.17	0.54	0+
	Ratio Caliper	1.44	0.33	0.30
	Mould	1.73	0.86	0+
Max HF df swing	Eyeball	0.82	0.54	0.01
	Ratio Caliper	0.63	0.33	0.24
	Mould	0.95	0.98	0+
Range HF df	Eyeball	2.16	1.32	0+
	Ratio Caliper	1.67	1.84	1.13
	Mould	1.48	0.59	0.36
Avg HF varus	Eyeball	3.97	6.06	0.68
	Ratio Caliper	1.99	4.07	0.98
	Mould	3.27	4.59	0.99
Avg HF rotation	Eyeball	2.43	1.72	4.79
	Ratio Caliper	2.43	4.65	0.03
	Mould	9.8	15.53	0+
Pooled*	Eyeball	2.32	2.10	1.48
	Ratio Caliper	1.63	2.24	0.54
	Mould	3.95	5.68	0+

*Pooled estimates were obtained allowing individual negative variances and so do not agree exactly with the means of the individual estimates in the table.
+ Negative estimate constrained to be zero.

4. Discussion

Overall our results show that in a healthy population, the ratio caliper method of marker placement produced the lowest intra-tester variability for the experienced gait analyst in all five variables and for the inexperienced gait analyst in four out of five variables (all but the transverse plane). However for inter-tester variability, the ratio caliper was only lower than the eyeball method in two out of the five variables. The mould produced the worst results for 3 of the 5 variables, and was particularly prone to variability when assessing average hindfoot rotation, making it the least reliable method overall. Therefore we can only partly accept our hypotheses.

The concept behind the heel mould was that it serves as a morphological template of the hindfoot. It's relatively poor results might be due to its maneuverability on the subject's foot. Despite having it available in three different sizes, there was medial/lateral play of the mould on the hindfoot when placing it on the subject in non-weight bearing which would have affected its repeatability. This was evident from outliers in the raw data using this method of marker placement causing occasional very wide deviations which affects the estimates of reliability. These outliers were examined and found to be true values for both gait analysts. However, even without these outlying observations, variability was still greater with this method.

Our analysis showed zero inter-rater variance components for 5 of the 15 combinations of variable and method. When these components are zero or very small, chance variation can result in inter-tester reliability being paradoxically better than intra-tester variability, as we saw in Fig. 1. Although surprising, we have also found this trend when analyzing the inter-tester repeatability of OFM marker placement in children with clubfoot, using an experienced and inexperienced gait analyst as well [9].

It is common practice to place the OFM using the eyeball method with palpation for marker placement for all segments. The Heidelberg foot measurement model uses a heel alignment device to place the medial and lateral calcaneal markers [6]. The authors describe its use in a non-weight bearing position with the main axis extending from the heel to the toe marker and the secondary axis aligned with the Achilles tendon. This may be appropriate in healthy populations, but in foot deformity the Achilles tendon is often mal-aligned in relation to the calcaneus; a common clinical picture of 'escape valgus'. Like Deschamps and colleagues [4], we believe the hindfoot markers should be placed in weight bearing, therefore using devices such as the mould or the

Heidelberg heel alignment device in non-weight bearing, may negatively affect the marker placement and therefore axis definition of a three-dimensional foot model. Since the ratio caliper is used in weight-bearing and seems useful in improving repeatability of the central HEE marker placement in this study, the use of this jig warrants further testing.

The inexperienced analyst was generally less repeatable compared to the experienced analyst for hindfoot varus and rotation. This could be due to reduced knowledge of anatomy during marker placement of the HEE and PCA markers.

It was surprising to the authors that the inexperienced gait analyst was the most repeatable with the eyeball method. This does reinforce the OFM's original design for marker placement and suggest the eyeball method can be used reliably with only six months of experience. Our data also suggests that a jig may not improve the repeatability for an inexperienced analyst. Maybe the task of placing a jig on a foot further complicates the task of marker placement for inexperienced analysts.

We recognise this study included a healthy adult population, a small sample size, only two raters, and all testing was completed on the same day. We would recommend this study be repeated comparing the eyeball method to the ratio caliper, with more gait analysts placing markers over different days, using a larger sample size including adults and children, with a range of foot postures. A population with foot deformity may yield different results due to difficulties with marker placement in abnormal standing anatomical alignment [9].

Since most kinematic multi-segment foot models use a posterior calcaneus marker to define the axes of the calcaneus [10], it is likely that the use of ratio caliper may help improve repeatability for placing this marker when using any foot model. This in turn can improve the sensitivity of the models to detect clinically meaningful differences in their populations. We would recommend this study be repeated comparing eyeball method to ratio caliper using other published foot models.

5. Conclusions

In a healthy adult population, the ratio caliper improved the intra-tester repeatability of hindfoot marker placement for an experienced and an inexperienced gait analyst. However, both ratio caliper and eyeballing yielded good inter-tester repeatability.

Declaration of Competing Interest

None

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.gaitpost.2021.01.006.

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