Title: Sensitivity of the Oxford Foot Model to marker misplacement: A systematic single-case investigation.

Authors

1. Christopher P. Carty^{1,2}
2. Henry PJ Walsh¹
3. Jarred G Gillett^{1,3}

Affiliations

¹ *Queensland Children's Motion Analysis Service, Children's Health Queensland Hospital and Health Service, Brisbane, Australia.*

² *Centre for Musculoskeletal Research & School of Allied Health Sciences, Griffith Health Institute, Gold Coast, Australia.*

³ *Queensland Cerebral Palsy and Rehabilitation Research Centre, School of Medicine, The University of Queensland Brisbane, Australia.*

Corresponding Author:

Christopher P Carty

Centre for Musculoskeletal Research & School of Allied Health Sciences

Griffith Health Institute

Griffith University

Griffith Location: Clinical Sciences 1 (G02), Parklands Drive, Southport, QLD 4215, Australia

Email: c.carty@griffith.edu.au

Key words: Oxford Foot Model, sensitivity, gait analysis.

Shortened title: Oxford Foot Model Sensitivity

Acknowledgements: Dr Carty was supported by a Griffith University Research Fellowship

Research highlights

- We undertook a sensitivity analysis of Oxford Foot Model marker misplacement
- The heel-wand complex had most pronounced effects across all degrees-of-freedom
- Vertical misplacement of P5M affected sagittal plane, hindfoot-tibia kinematics
- D5M and P5M affected sagittal plane, forefoot-hindfoot kinematics

Abstract

The purpose of this paper was to systematically assess the effect of Oxford Foot Model (OFM) marker misplacement on hindfoot relative to tibia, and forefoot relative to hindfoot kinematic calculations during the stance phase of gait. Marker trajectories were recorded with an 8-camera motion analysis system (Vicon Motion Systems Ltd, UK) and ground reaction forces were recorded from three force platforms (AMTI, USA). A custom built marker cluster consisting of 4 markers in a square arrangement (diagonal distance 2cm) was used to assess the effect of marker misplacement in the superior, inferior, anterior and posterior direction for the sustentaculum tali (STL), the proximal 1st metatarsal (P1M), distal 5th metatarsal (D5M), proximal 5th metatarsal (P5M) and lateral calcaneus (LCA) markers. In addition manual movement of the heel complex 1cm superiorly, inferiorly, medially and laterally, and also an alignment error of 10 degrees inversion and 10 degrees eversion was assessed. Clinically meaningful effects of marker misplacement were determined using a threshold indicating the minimal clinically important difference. Misplacement of the heel-wand complex had the most pronounced effect on mean kinematic profiles during the stance phase across all degrees-of-freedom with respect to hindfoot-tibia and forefoot-hindfoot angles. Vertical marker misplacement of the D5M and P5M markers affected the sagittal plane, and to a lesser extent frontal plane, forefoot-hindfoot kinematics. In conclusion, the OFM is highly sensitive to misplacement of the heel-wand complex in all directions and the P5M marker in the vertical direction.

Introduction

The conventional gait model (CGM) [1-3] does not provide adequate detail on foot kinematics to make an informed surgical decision for children with foot pathology. To overcome this limitation a number of clinical gait laboratories have implemented complementary analyses including multi-segment foot modelling and pedobarography, and in some instances an integration of both [4]. Multi-segment foot modelling can provide meaningful information to guide bone and soft tissue intervention around the ankle-foot complex [5], however, unlike the CGM there is currently no consensus on a standardised marker set or model [6-8]. The Oxford Foot Model (OFM) [9-11] is gaining popularity in clinical gait laboratories due to its availability as a Plug-in to complement the CGM in Vicon Nexus (Vicon Motion Systems Ltd, UK). There is evidence that the OFM is reliable **in both adult** [9, 12] and paediatric [10, 13] populations. **Furthermore, there is emerging work on the impact of marker misplacement using artificial corrections based on CT scans indicating that the anterior-posterior axis of the hindfoot segment in the OFM is most sensitive to the location of the heel marker** [14]. To date, a systematic sensitivity analysis of marker misplacement using the OFM has not been undertaken. Given the relative size of the paediatric foot and the multiple degrees-of-freedom prescribed in the OFM it is likely that small errors in marker placement will have a clinically meaningful effect on kinematic profiles. **A recent study has shown that inter-tester variability in the manual placement of the calcaneal markers by experienced physicians was approximately 6mm indicating that it can be difficult to position markers on the foot** [15]. The purpose of this paper was to systematically assess the effect of OFM marker misplacement on hindfoot relative to tibia, and forefoot relative to hindfoot kinematic calculations during the stance phase of gait. We

hypothesised that the OFM will be most sensitive to misplacement of the heel-wand marker complex.

Methods

Participants

One typically developed participant (height=156cm, mass=52 kg, foot length=21.5cm) volunteered. Ethical clearance and informed consent were obtained.

Data capture

The Plug-in-Gait and OFM marker sets were attached in accordance with Vicon release notes by an experienced therapist. Marker trajectories were recorded at 100Hz using an 8-camera, three-dimensional motion analysis system (MX40 cameras, Vicon Motion Systems Ltd, UK) and ground reaction forces were simultaneously acquired at 1KHz from three force platforms (510mm×465mm, AMTI, USA) arranged in series in the centre of the walkway. Following a static calibration trial, the participant was asked to walk at a self-selected speed along the walkway. For the sensitivity analysis a custom built marker cluster consisting of four markers in a square arrangement was developed. Markers diagonally opposite on the cluster were separated by 2cm and the centroid of the area was identified by a hollow circle (2mm diameter). **The marker cluster allowed assessment of marker misplacement of 1cm in four directions, representing a magnitude slightly higher than previously documented inter-therapist marker placement variability for foot marker placement [15].** Following the gait assessment using the standard OFM marker placement the STL marker was replaced with the marker cluster. **The centroid of the cluster was positioned at the palpated marker location (Figure 1A) by a single investigator and was rotated about the centroid to represent marker misplacement errors of 1cm in superior, inferior, anterior and**

posterior directions. Once the cluster was positioned, three of the four markers were masked using non-reflective covers and the static calibration and walk trials were repeated as described above. This entire process was repeated for the proximal 1st metatarsal (P1M), distal 5th metatarsal (D5M), proximal 5th metatarsal (P5M) and lateral calcaneus (LCA) markers (Figure 1B-E). The collection process was additionally repeated following manual movement of the heel-wand complex (comprising the heel and calcaneal wand markers) to determine the effect of marker misplacement 1cm superiorly, inferiorly, medially and laterally, and also an alignment error of 10 degrees inversion and eversion. **To induce the alignment error the borders of the calcaneus and a bisecting line were drawn on the surface of the heel to establish the original position for the heel-wand complex. The heel-wand complex was then aligned in 10 degrees of inversion and eversion using a goniometer.** A second standard collection was undertaken with all markers in their initial position to determine any effects of slight marker misplacement in the reattachment of markers during the testing protocol. All marker placements were performed by the same therapist.

Kinematic calculation and data analysis

Marker trajectories and ground reaction force data were filtered using a 4th order, zero-lag, low-pass, Butterworth filter (cut-off at 6Hz). Joint kinematic calculations were performed using the Plug-in-Gait model and the OFM Plug-in using Vicon Nexus (v1.8.5, Vicon Motion Systems Ltd, UK). Kinematic waveforms for the hindfoot relative to the tibia, and the forefoot relative to the hindfoot were imported into Matlab (v2013b, Mathworks, USA) using the biomechanics tool kit [16]. The mean angle ($\pm$ 1SD) during the stance phase was computed for each degree-of-freedom across four gait cycles for each of the conditions described above. The difference between the standard OFM marker placement and the

prescribed marker errors was calculated as the mean RMS difference from the standard curve across the stance phase. To determine whether marker placement errors had a clinically meaningful effect on data interpretation a threshold was placed on each plot indicating the minimal clinically important difference ($MCID = 1.96 \times SEM \times \sqrt{2}$), where SEM represents the standard error of the measure previously documented for the OFM [12].

Results

Kinematic profiles for the standard OFM marker placement were within the typical range for hindfoot-tibia and forefoot-hindfoot angles previously reported for healthy children [10] (see supplementary figure 1). Walking velocity was consistent across the 28 gait sessions (1.14 ± 0.03 m/s).

Hindfoot-tibia sensitivity

The effect of marker misplacement on hindfoot relative to tibia angles is shown in Figure 2A-C. In the sagittal plane, inversion, eversion, superior and inferior placement of the heel-wand complex, and superior and inferior placement of the P5M marker led to differences above the MCID threshold. In the transverse plane, inversion, eversion, medial and lateral placement of the heel-wand complex led to differences above the MCID threshold. In the frontal plane inversion and eversion of the heel-wand complex led to differences above the MCID threshold.

Forefoot-hindfoot sensitivity

The effect of marker misplacement on forefoot relative to hindfoot angles is shown in Figure 2D-F. In the sagittal plane, superior and inferior placement of the heel-wand complex, D5M and P5M markers led to differences above the MCID threshold. In the transverse plane,

medial and lateral placement of the heel-wand complex led to differences above the MCID threshold. In the frontal plane, inversion, eversion and lateral placement of the heel-wand complex and inferior placement of the D5M marker led to differences above the MCID threshold.

Discussion

We systematically assessed whether OFM marker misplacement led to clinically meaningful changes in kinematic calculations. In agreement with our hypothesis, errors in placement of the heel-wand complex had the most pronounced effect on mean kinematic profiles during the stance phase across all degrees-of-freedom. This finding is in agreement with Paik et al. [14] who reported the anterior-posterior axis of the hindfoot to be most sensitive to the location of the heel marker compared to the LCA and STL markers. **Therefore it is important to standardise positioning of the heel marker. This could be done by using a mechanical guidance device like the Calcaneal Marker Device described by Deschamps et al. [15] which has been shown to improve inter- and intra-therapist marker placement variability.** An unanticipated finding was that vertical marker placement error of the P5M marker also affected sagittal plane hindfoot relative to tibia kinematics. This might be due to the static calibration step in the OFM Plug-in whereby the heel and P5M markers are used to define in the anterior-posterior axis of the hindfoot. As expected, misplacement of the heel-wand complex also affected forefoot relative to hindfoot angles due their above mentioned effect on hindfoot alignment. In addition to the heel-wand complex, misplacement of the D5M and P5M markers in the vertical direction affected forefoot-tibia angles in the sagittal plane and to a lesser extent, in the frontal plane (superior positioning on D5M only) due to the impact these markers have on the anatomical definition of the forefoot [10]. **A consideration in interpreting the results of this study is that any multi-segment foot**

model that relies on skin mounted markers to track the motion of the underlying bone is subject to error, and this error is not uniform across foot marker locations [17].

Furthermore, the reference values for SEM were from an adult population and it would be expected that children are slightly more variable. It is important to note that the sensitivity of kinematic output to marker misplacement may vary with larger or smaller foot size compared to the foot of the participant in this study (21.5cm). In conclusion, the OFM is highly sensitive to misplacement of the heel-wand complex in all directions and the P5M marker in the vertical direction. It is recommended that care be taken to ensure that these markers are positioned accurately and that video footage is captured to cross-check kinematic profiles with marker placements.

Figure captions

Figure 1. Position of the cluster on each of the marker positions as follows: (A) sustentaculum tali (STL), (B) proximal 1st metatarsal (P1M), (C) distal 5th metatarsal (D5M), (D) proximal 5th metatarsal (P5M) and (E) lateral calcaneus marker (LCA) markers.

Figure 2. The effect of marker misplacement on hindfoot relative to tibia angles in the sagittal, transverse and frontal planes and, the effect of marker misplacement on forefoot relative to hindfoot angles tibia angles in the sagittal, transverse and frontal planes. Bars represent the mean RMS difference from the standard curve across the stance phase for marker misplacement as follows: baseline standard marker placement, post sensitivity testing standard marker placement, Heel-wand complex (Heel) misplacement (inversion, eversion, superior, inferior, medial and lateral), sustentaculum tali (STL) misplacement (superior, inferior, anterior, posterior), proximal 1st metatarsal (P1M) misplacement (superior, inferior, anterior, posterior), distal 5th metatarsal (D5M)) misplacement (superior, inferior, anterior, posterior), proximal 5th metatarsal (P5M) misplacement (superior, inferior, anterior, posterior), and lateral calcaneus (LCA) misplacement (superior, inferior, anterior, posterior). Horizontal line (--) represents the threshold for a minimal clinically important difference ($MCID = 1.96 \times SEM \times \sqrt{2}$), where SEM represents the standard error of the measure previous document for the OFM [12].

References

- [1] Davis RB, Ounpuu S, Tyburski D, Gage JR. A gait analysis data collection and reduction technique. *Human Movement Science*. 1991;10:575-87.
- [2] Kadaba MP, Ramakrishnan HK, Wootten ME. Measurement of lower extremity kinematics during level walking. *Journal of orthopaedic research : official publication of the Orthopaedic Research Society*. 1990;8:383-92.
- [3] Kadaba MP, Ramakrishnan HK, Wootten ME, Gaine J, Gorton G, Cochran GV. Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. *Journal of orthopaedic research : official publication of the Orthopaedic Research Society*. 1989;7:849-60.
- [4] Giacomozzi C, Leardini A, Caravaggi P. Correlates between kinematics and baropodometric measurements for an integrated in-vivo assessment of the segmental foot function in gait. *Journal of biomechanics*. 2014;47:2654-9.
- [5] Theologis T, Stebbins J. The use of gait analysis in the treatment of pediatric foot and ankle disorders. *Foot and ankle clinics*. 2010;15:365-82.
- [6] Bishop C, Paul G, Thewlis D. Recommendations for the reporting of foot and ankle models. *Journal of biomechanics*. 2012;45:2185-94.
- [7] Deschamps K, Staes F, Roosen P, Nobels F, Desloovere K, Bruyninckx H, et al. Body of evidence supporting the clinical use of 3D multisegment foot models: a systematic review. *Gait & posture*. 2011;33:338-49.
- [8] Saraswat P, MacWilliams BA, Davis RB, D'Astous JL. A multi-segment foot model based on anatomically registered technical coordinate systems: method repeatability and sensitivity in pediatric planovalgus feet. *Gait & posture*. 2013;37:121-5.

- [9] Carson MC, Harrington ME, Thompson N, O'Connor JJ, Theologis TN. Kinematic analysis of a multi-segment foot model for research and clinical applications: a repeatability analysis. *Journal of biomechanics*. 2001;34:1299-307.
- [10] Stebbins J, Harrington M, Thompson N, Zavatsky A, Theologis T. Repeatability of a model for measuring multi-segment foot kinematics in children. *Gait & posture*. 2006;23:401-10.
- [11] Theologis TN, Harrington ME, Thompson N, Benson MK. Dynamic foot movement in children treated for congenital talipes equinovarus. *The Journal of bone and joint surgery British volume*. 2003;85:572-7.
- [12] Wright CJ, Arnold BL, Coffey TG, Pidcoe PE. Repeatability of the modified Oxford foot model during gait in healthy adults. *Gait & posture*. 2011;33:108-12.
- [13] Mahaffey R, Morrison SC, Drechsler WI, Cramp MC. Evaluation of multi-segmental kinematic modelling in the paediatric foot using three concurrent foot models. *Journal of foot and ankle research*. 2013;6:43.
- [14] Paik AMH, Stebbins J, Kothari A, Zavatsky AB. Effect of marker placement on Oxford Foot Model hindfoot segment axes. 4th Congress of the International Foot and Ankle Biomechanics (i-FAB) Community. Busan, Korea2014.
- [15] Deschamps K, Roosen P, Birch I, Dingenen B, Bruyninckx H, Desloovere K, et al. A novel device for standardizing marker placement at the calcaneus. *Journal of the American Podiatric Medical Association*. 2014;104:43-9.
- [16] Barre A, Armand S. Biomechanical ToolKit: Open-source framework to visualize and process biomechanical data. *Computer methods and programs in biomedicine*. 2014;114:80-7.
- [17] Birch I, Deschamps K. Quantification of skin marker movement at the malleoli and talar heads. *Journal of the American Podiatric Medical Association*. 2011;101:497-504.

Figure 2

Accepted Manuscript

Title: Sensitivity of the Oxford Foot Model to marker misplacement: A systematic single-case investigation

Author: Christopher P. Carty Henry PJ Walsh Jarred G Gillett

PII: S0966-6362(15)00691-8

DOI: <http://dx.doi.org/doi:10.1016/j.gaitpost.2015.06.189>

Reference: GAIPOS 4514

To appear in: *Gait & Posture*

Received date: 27-2-2015

Revised date: 18-6-2015

Accepted date: 23-6-2015

Please cite this article as: Carty CP, Walsh HPJ, Gillett JG, Sensitivity of the Oxford Foot Model to marker misplacement: A systematic single-case investigation, *Gait and Posture* (2015), <http://dx.doi.org/10.1016/j.gaitpost.2015.06.189>

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.