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Marker placement sensitivity of the Oxford and Rizzoli foot models in adults and children

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ABSTRACT

Understanding the effect of individual marker misplacements is important to improve the repeatability and aid to the interpretation of multi-segment foot models like the Oxford and Rizzoli Foot Models (OFM, RFM). Therefore, this study aimed to quantify the effect of controlled anatomical marker misplacement on multi-segment foot kinematics (i.e. marker placement sensitivity) as calculated by OFM and RFM in a range of foot sizes. Ten healthy adults and nine children were included. A combined OFM and RFM marker set was placed on their right foot and a static standing trial was collected. Each marker was replaced $\pm$ 10 mm in steps of 1 mm over the three axes of a foot coordinate system. For each replacement the change in segment orientation (tibia, hindfoot, midfoot, forefoot) was calculated with respect to the reference pose in which no markers were replaced. A linear fit was made to calculate the sensitivity of segment orientation to marker misplacement in °/mm. Additionally, the effect of foot size on the sensitivity was determined using linear regressions. For every foot segment of both models, at least one marker had a sensitivity $\geq$ 1.0°/mm. Highest values were found for the markers at the posterior aspect of the calcaneus in OFM (1.5°/mm) and the basis of the second metatarsal in RFM (1.4°/mm). Foot size had a small effect on 40% of the sensitivity values. This study identified markers of which consistent placement is critical to prevent clinically relevant errors (>5°). For more repeatable multi-segment models, the role of these markers within the models' definitions needs to be reconsidered.

1. Introduction

Foot and ankle problems during gait are regularly assessed with 3-dimensional (3D) marker-based gait analyses. Conventionally, mono-segment foot models are used in gait analyses, which consider the foot as one rigid segment (Cappozzo et al., 1995; Davis et al., 1991). However, mono-segment foot models overestimate the ankle angle in the sagittal plane (Pothrat et al., 2015) and neglect motions between segments within the foot. Hence, over the last years, several multi-segment foot models have been developed (Leardini et al., 2019), which divide the foot into multiple segments. The Oxford Foot Model (OFM) (Stebbins et al., 2006) and Rizzoli Foot Model (RFM) (Leardini et al., 2007) are the two most frequently used multi-segment foot models both in research and clinical practice (Leardini et al., 2019).

Consistent and anatomically accurate placement of markers that define the anatomical coordinate systems is critical to obtain reliable and meaningful joint kinematics (Della Croce et al., 2005). Clinical decision-making depends on this consistent and accurate marker placement. In multi-segment foot models, the repeatability between days or testers is primarily subject to variability of marker placement (Carson et al., 2001). This variability is reported to be around 5 mm, with outliers up to 13 mm between testers (Bishop et al., 2013; Deschamps et al., 2014). The repeatability of OFM and RFM kinematics has been assessed frequently in both healthy and pathological populations (Caravaggi et al., 2011; Deschamps et al., 2012; Di Marco et al., 2016; Mahaffey et al., 2013; McCahill et al., 2018; Stebbins et al., 2006).

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In these studies, all markers were replaced simultaneously, thereby mainly evaluating the variability in performance of the tester. However, insight in the effect of misplacement of individual markers on the multi-segment foot kinematics (i.e. its sensitivity) is limited, while it highlights which marker placements are most critical and should be placed with extra caution. One preliminary study using CT scans, found that the anterior-posterior axis of the hindfoot segment in OFM was most sensitive to misplacement of the heel marker (Paik et al., 2014). Another study did systematically asses the sensitivity of OFM to the misplacement of a subset of its markers, by using marker clusters that simulate misplacement of 1 cm in four directions (Carty et al., 2015). Misplacements of the marker proximally on the 5th metatarsal and of the heel marker were shown to cause the highest kinematic errors in gait trials. However, as mentioned by the authors themselves, only one foot was included while the sensitivity values are likely to vary over different feet, especially concerning their size. Even though OFM and RFM are the most frequently used multi-segment foot models, the marker placement sensitivity has never been studied for RFM and only in part for OFM for just a single foot. Therefore the aim of this study is to quantify the marker misplacement sensitivity of multi-segment foot kinematics as measured by OFM and RFM in a range of foot sizes.

2. Methods

2.1. Participants

Ten healthy adults (6 female, 26.8 ± 2.6 years, 176.4 ± 8.1 cm, 67.2 ± 8.5 kg, EU shoe size: 41 ± 2, range 38–45) and nine typically-developed children (5 female, 10.7 ± 1.9 years, 147.7 ± 12.8 cm, 41.1 ± 10.9 kg, EU shoe size: 36 ± 2, range: 31–38) were included in this study, in order to cover a range of foot sizes. The subjects did not wear insoles, nor had foot or ankle complaints in the last year. Informed consent was signed by all subjects older than 11 and by their parents for subjects younger than 17. Ethical approval was provided by the local ethics committee.

2.2. Data collection

Passive retroreflective markers were placed on the lower extremities of the subjects according to the Newington marker model (Davis et al., 1991). A combined OFM (Stebbins et al., 2006) and RFM (Leardini et al., 2007) marker set was placed on their right foot and shank, which consisted of 21 markers (Table 1, Fig. 1). The RFM marker on the head of the 2nd metatarsal could not be placed because of its proximity to the OFM marker in between the 2nd and 3rd metatarsal head and was therefore replaced in the RFM calculation by the latter, as in other studies (Mahaffey et al., 2013; Schallig et al., 2020). The markers on the feet of the children and adults were placed by two different testers. One static standing trial was performed, during which the 3D marker positions were recorded by a 12-camera motion capture system (Vicon Motion Systems Ltd., Oxford, UK).

2.3. Data processing and analysis

The effect of marker misplacement on the segment orientations was calculated separately for every segment of OFM (Stebbins et al., 2006) and RFM (Leardini et al., 2007) in Matlab (R2017b, MathWorks, USA). The shank-, hindfoot- and forefoot segment were evaluated for both models and the midfoot segment only for RFM. First, a foot coordinate system (FCS) was defined as in Cappozzo et al. (1995) based on the marker proximally on the posterior aspect of the calcaneus (CALP) and the markers on the heads of the 1st, 5th and in between the 2nd and 3rd metatarsal (HM1, HM5 and HM23), which provided a foot-specific anterior-posterior (x), superior-inferior (y) and medio-lateral (z) axis. Next, one by one, each marker was virtually replaced ± 10 mm, in steps of 1 mm, over the x-, y- and z-axis of the FCS. This resulted in sixty replacements for each marker. For every replacement, the anatomical segment coordinate system (SCS) was redetermined and its orientation was calculated with respect to the SCS in the reference pose in which no markers were moved. The resulting rotation matrix was decomposed according to Grood and Suntay (1983) to obtain three angular errors, referred to as in the sagittal, frontal and transverse plane.

Table 1
Overview of the foot model markers used in this study.

Segment	Marker Number	Marker placement	Abbreviation	OFM	RFM
Shank	1	Anterior aspect of shin	SHIN	x	
	2	Tibial tuberosity	TTIB	x	x
	3	Fibula head	HFIB	x	x
	4	Medial malleolus	MMAL	x	x
	5	Lateral malleolus	LMAL	x	x
Hindfoot	6	Posterior aspect calcaneus proximal	CALP	x	x
	7	Posterior aspect calcaneus distal	HEE	x	x
	8	Medial calcaneus	MCAL	x	
	9	Lateral calcaneus	LCAL	x	
	10	Peroneal tubercle	PTU		x
	11	Sustentaculum tali	STL		x
Midfoot	12	Medial apex tuberosity of navicular	NAV		x
Forefoot	13	Base metatarsal 1	BM1	x	x
	14	Head metatarsal 1	HM1		x
	15	Head metatarsal 1 medial	HM1M	x	
	16	Head metatarsal 5	HM5	x	x
	17	Base metatarsal 5	BM5	x	x
	18	Halfway between 2nd and 3rd metatarsal head	HM23	x	x*
	19	Base metatarsal 2	BM2		x
Hallux	20	Head of proximal phalanx of hallux medial	HLX	x	
	21	Head of proximal phalanx of hallux dorsal	BHLX		x

* Not according to model definitions of RFM which would rather place it on the 2nd metatarsal; however it was not possible to combine this with the OFM marker set.

Next, marker placement sensitivity was determined for the marker replacement in each of the three replacement directions for each of the three anatomical planes. A linear fit was made over the angular error between −10 and 10 mm displacement. The gradient of this line was defined as the marker placement sensitivity in degrees per mm for that specific replacement direction and anatomical plane (Fig. 2A). Furthermore, the effect of foot size on the sensitivity values was assessed by performing simple linear regressions using the least square method in Matlab for each marker in each plane (Fig. 2B). Foot size was calculated as the distance between the HEE and BHLX markers projected to the ground. Regression coefficients described how the marker sensitivity changed when the foot size was 1 cm larger and are only presented when significant ($p < 0.05$).

3. Results

The nine sensitivity values for each marker of OFM and RFM and the corresponding effect of foot size on these values are shown in Table 2 and 3. In total, 69% of the sensitivity values were ≤ 0.2°/mm, indicating that the segment orientation changed < 0.2° when a marker was misplaced one mm. However, for each marker at least one sensitivity value of ≥ 0.5°/mm was present. Moreover, every foot segment of both models, had at least one marker with a placement sensitivity of ≥ 1.0°/mm.

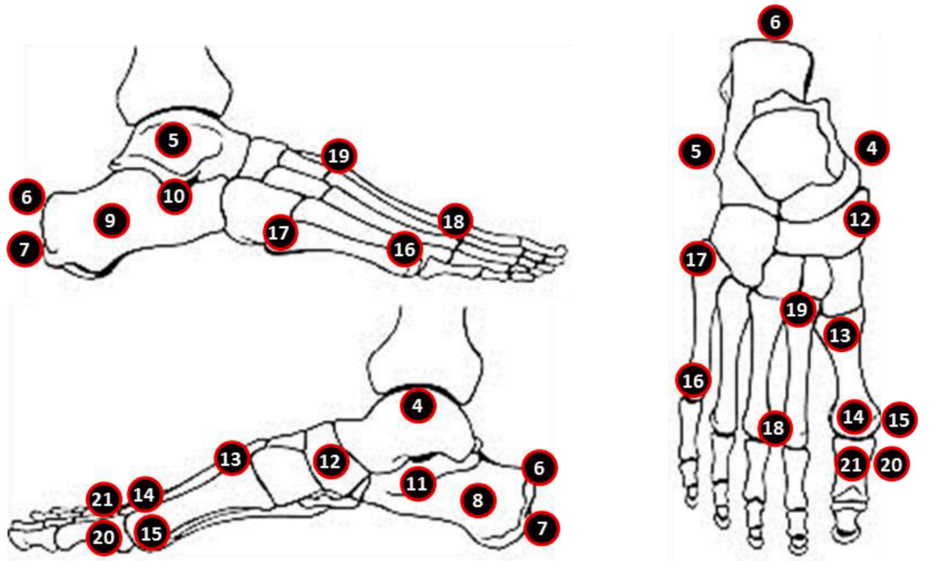

Fig. 1. Schematic **o**verview of the marker placements. Marker names and locations associated with the numbers can be found in table 1. Specific foot model definitions are described in Schallig et al. (2020).

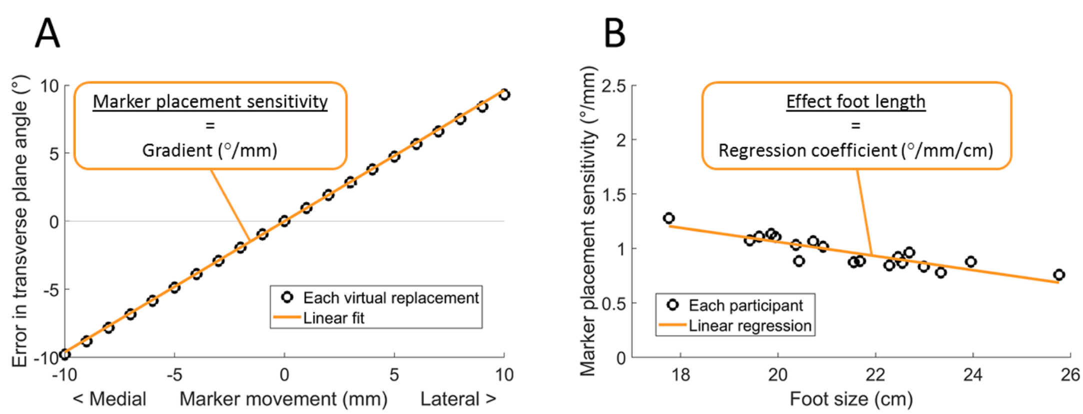

Fig. 2. An example of how the marker placement sensitivity (A) and the effect of foot size on this sensitivity (B) were determined. This is a specific example for the CALP marker in RFM, when replaced in lateral-medial direction, on the error in the transverse plane. The same analyses were performed for the error in the sagittal and frontal plane and for the other directions of marker movement (i.e. anterior-posterior and superior-inferior) for each of the markers. (A) To determine the marker placement sensitivity of a marker, a linear line was fitted through the angular errors in segment orientation. Its gradient was the marker placement sensitivity in °/mm. (B) The effect of foot size was assessed by performing a linear regression on the sensitivity values of all participants. The regression coefficient provided information about the change in marker placement sensitivity for every cm larger foot size.

In OFM, when misplacing the HEE marker in medio-lateral direction, mainly the orientation of the hindfoot in the frontal and transverse plane was affected (means: −1.4 and 1.5°/mm). The orientation in the frontal plane was also sensitive to misplacement of CALP in medio-lateral direction (mean: 1.5°/mm). The forefoot orientation in the sagittal plane was most sensitive to superior-inferior misplacement of the HM5 and BM5 markers (means: −1.1 and 1.0°/mm) and in the transverse plane for medio-lateral misplacement of the HM23 marker (mean: −1.0°/mm).

In RFM, the hindfoot orientation in the sagittal plane was mainly sensitive to superior-inferior misplacement of the CALP marker (mean: −1.0°/mm), in the frontal plane for superior-inferior misplacement of the PTU marker (mean: −0.9°/mm) and in the transverse plane for medio-lateral movement of the CALP marker (mean: 1.0°/mm). The largest marker placement sensitivity values for the midfoot orientation were found when misplacing the BM2 marker in any direction. The forefoot orientation of RFM was most sensitive in the transverse plane to misplacing the BM2 or HM23 marker in medio-lateral direction (means: 1.4 and −1.4°/mm). The shank orientation of both models was mainly sensitive in the transverse plane to anterior-posterior misplacement of the malleoli markers (means: ±0.7°/mm).

In total, 40.3% of the sensitivity values were influenced significantly by foot size. In most cases, a larger foot resulted in a smaller marker placement sensitivity (i.e. closer to zero), indicated by a regression coefficient opposite in sign to the marker sensitivity value (Table 2). All regression coefficients were ≤±0.10°/mm/cm, and most of those (94%) were ≤±0.07°/mm/cm, which means that the sensitivity values changed 0.10° or less per cm larger or smaller foot size. For OFM, largest values were found for the sensitivity of the hindfoot orientation in the frontal plane when misplacing the HEE or CALP marker in medio-lateral direction (±0.06°/mm/cm) and for the forefoot orientation in the sagittal plane when misplacing the HM5 or BM5 marker in superior-inferior direction (0.06 and −0.07°/mm/cm). For RFM, the hindfoot orientation sensitivity values were mainly influenced by foot size for superior-inferior and medio-lateral misplacement of the CALP marker (±0.06°/mm/cm). Forefoot orientation sensitivity values were mainly influenced by foot size for the BM2 marker when misplaced in any direction and the HM23 marker when misplaced in anterior-posterior

Table 2
Marker placement sensitivity presented as mean ± SD for the Oxford Foot Model (OFM). In case of a significant linear regression between the sensitivity values and foot size, the regression coefficient is shown, which provides information about how the sensitivity values change when the foot is 1 cm longer compared to the average foot size of 21.5 cm. Positive values indicate dorsal flexion, inversion, internal rotation and adduction.

			Marker Sensitivity (°/mm)			Effect foot size (°/mm/cm)		
Segment	Marker	Repl. direc.	Sagittal	Frontal	Transverse	Sagittal	Frontal	Transverse
Shank	MMAL	Ant./Post.	0.07±0.00	0.01±0.01	-0.71±0.05	-	-	0.024
		Sup./Inf.	0.01±0.00	-0.01±0.00	-0.14±0.05	-	0.001	-
		Lat./Med.	0.01±0.01	-0.07±0.00	-0.09±0.07	-	-	-
	LMAL	Ant./Post.	0.07±0.00	0.01±0.01	0.68±0.05	-	-	-0.022
		Sup./Inf.	0.01±0.00	-0.01±0.00	0.14±0.05	-	0.001	-
		Lat./Med.	0.01±0.01	-0.07±0.00	0.08±0.07	-	-	-
Hindfoot	HEE	Ant./Post.	0.10±0.05	-0.03±0.07	0.03±0.07	-0.021	-	-
		Sup./Inf.	-0.63±0.08	-0.22±0.08	0.23±0.08	0.031	-	-0.021
		Lat./Med.	-0.44±0.13	-1.35±0.22	1.43±0.14	-0.038	-0.056	-
	CALP	Ant./Post.	0.02±0.03	0.04±0.07	0.00±0.01	-	-	-
		Sup./Inf.	0.10±0.04	0.24±0.09	0.01±0.02	-	-	-
		Lat./Med.	0.59±0.11	1.52±0.19	0.01±0.12	-	0.057	-
	LCAL	Ant./Post.	0.00±0.00	0.00±0.00	-0.02±0.04	-	-	-
		Sup./Inf.	-0.01±0.00	-0.01±0.01	-0.12±0.05	-	-	0.013
		Lat./Med.	-0.03±0.02	-0.08±0.06	-0.75±0.04	-	-	-
	MCAL	Ant./Post.	0.00±0.00	0.00±0.00	-0.02±0.04	-	-	-
		Sup./Inf.	-0.01±0.00	-0.01±0.01	-0.12±0.05	-	-	0.013
		Lat./Med.	-0.03±0.02	-0.08±0.06	-0.75±0.04	-	-	-
	BM5	Ant./Post.	-0.12±0.04	0.00±0.00	0.00±0.00	0.019	-	-
		Sup./Inf.	0.53±0.06	0.00±0.00	0.00±0.00	-0.026	-	-
		Lat./Med.	-0.08±0.04	0.00±0.00	0.00±0.00	0.013	-	-
Forefoot	BM1	Ant./Post.	0.00±0.00	0.00±0.00	0.01±0.03	-	-	0.010
		Sup./Inf.	0.00±0.00	0.00±0.00	0.02±0.01	-	-	-
		Lat./Med.	0.00±0.00	0.00±0.00	0.50±0.04	-	-	-
	HM5	Ant./Post.	0.23±0.07	-0.05±0.02	0.01±0.03	-0.025	-	0.011
		Sup./Inf.	-1.06±0.15	0.24±0.09	0.04±0.02	0.062	0.024	-
		Lat./Med.	0.04±0.02	-0.01±0.01	0.50±0.04	-	-	-
	HM1M	Ant./Post.	-0.02±0.01	-0.11±0.04	-0.01±0.01	-	0.011	0.004
		Sup./Inf.	0.08±0.03	0.54±0.05	0.05±0.05	-	-0.021	-0.015
		Lat./Med.	0.00±0.00	-0.02±0.01	0.00±0.00	-	-	0.001
	BM5	Ant./Post.	-0.21±0.07	0.17±0.05	0.01±0.01	0.026	-	-0.004
		Sup./Inf.	0.97±0.17	-0.78±0.07	-0.07±0.07	-0.069	-	0.019
		Lat./Med.	-0.04±0.02	0.03±0.02	0.00±0.00	-	-	-0.001
	HM23	Ant./Post.	0.00±0.00	0.00±0.00	-0.03±0.07	-	-	-0.020
		Sup./Inf.	0.00±0.00	0.00±0.00	-0.05±0.02	-	-	-
		Lat./Med.	0.00±0.00	0.00±0.00	-0.99±0.07	-	-	-

Note: Marker abbreviations are explained in Table 1. The replacement direction (repl. direc.) is in anterior/posterior (Ant./Post.), superior/inferior (Sup./Inf) and Lat./Med.) direction, of which the first is in positive direction.
Color coding: linear distribution from lowest (white) to absolute highest (red or blue) value of both models as in the following: and

Table 3
Marker placement sensitivity presented as mean ± SD for the Rizzoli Foot Model (RFM). In case of a significant linear regression between the sensitivity values and foot size, the regression coefficient is shown, which provides information about how the sensitivity values changes when the foot is 1 cm longer compared to the average foot size of 21.48 cm. Positive values are dorsal flexion, inversion, internal rotation and adduction.

			Marker Sensitivity (°/mm)			Effect foot size (°/mm/cm)		
Segment	Marker	Repl. direc.	Sagittal	Frontal	Transverse	Sagittal	Frontal	Transverse
Shank	MMAL	Ant./Post.	-0.06±0.01	-0.06±0.03	-0.68±0.04	-	-	0.020
		Sup./Inf.	-0.01±0.01	-0.03±0.01	-0.12±0.05	-	0.005	0.014
		Lat./Med.	-0.01±0.01	-0.10±0.01	-0.08±0.07	-	0.005	-
	LMAL	Ant./Post.	0.22±0.03	0.08±0.02	0.65±0.04	-0.011	-	-0.017
		Sup./Inf.	0.04±0.02	0.00±0.01	0.12±0.05	-0.006	-	-0.013
		Lat./Med.	0.03±0.02	-0.08±0.02	0.08±0.06	-	0.006	-
Hindfoot	CALP	Ant./Post.	-0.03±0.15	0.00±0.04	0.09±0.05	0.053	-0.010	-
		Sup./Inf.	-0.95±0.13	0.22±0.10	-0.01±0.07	0.061	-	-
		Lat./Med.	-0.01±0.07	0.01±0.02	0.96±0.14	-	-	-0.065
	STL	Ant./Post.	0.02±0.07	0.02±0.10	-0.04±0.03	-0.026	-0.038	-
		Sup./Inf.	0.48±0.07	0.69±0.09	0.01±0.03	-0.031	-0.039	-
		Lat./Med.	0.01±0.04	0.01±0.05	-0.48±0.07	-	-	0.033
	PTU	Ant./Post.	0.02±0.07	-0.03±0.14	-0.04±0.03	-0.026	0.048	-
		Sup./Inf.	0.48±0.07	-0.91±0.10	0.01±0.03	-0.031	0.033	-
		Lat./Med.	0.01±0.04	-0.01±0.07	-0.48±0.07	-	-	0.033
Midfoot	BM2	Ant./Post.	-0.87±0.18	0.06±0.09	-0.16±0.19	-	-	0.067
		Sup./Inf.	0.89±0.10	-0.06±0.09	0.18±0.16	0.024	-	0.051
		Lat./Med.	0.24±0.12	-0.02±0.04	-1.21±0.15	-	-	-0.038
	NAV	Ant./Post.	0.43±0.09	-0.47±0.09	0.08±0.09	-	0.027	-0.033
		Sup./Inf.	-0.44±0.05	0.48±0.08	-0.09±0.08	-0.012	-0.028	-0.025
		Lat./Med.	-0.12±0.06	0.14±0.08	0.61±0.07	-	-0.020	0.019
	BM5	Ant./Post.	0.43±0.09	0.41±0.06	0.08±0.09	-	-	-0.033
		Sup./Inf.	-0.44±0.05	-0.42±0.07	-0.09±0.08	-0.012	-	-0.025
		Lat./Med.	-0.12±0.06	-0.12±0.06	0.61±0.08	-	-	0.019
Forefoot	BM2	Ant./Post.	-0.64±0.16	0.11±0.12	-0.12±0.25	-	0.047	0.101
		Sup./Inf.	-1.20±0.19	0.20±0.21	-0.36±0.07	0.077	0.090	-
		Lat./Med.	-0.44±0.10	0.07±0.08	1.36±0.18	0.043	0.032	-
	HM5	Ant./Post.	0.26±0.07	-0.32±0.08	-0.09±0.04	-	-	-
		Sup./Inf.	0.49±0.07	-0.62±0.06	-0.16±0.03	-	-	-
		Lat./Med.	0.18±0.04	-0.23±0.03	-0.06±0.02	-0.011	-	-
	HM1	Ant./Post.	0.37±0.10	0.22±0.09	0.06±0.03	-0.023	-0.034	-0.013
		Sup./Inf.	0.71±0.14	0.42±0.17	0.11±0.06	-0.062	-0.076	-0.026
		Lat./Med.	0.26±0.07	0.16±0.08	0.04±0.02	-0.032	-0.034	-0.011
	HM23	Ant./Post.	0.00±0.00	0.00±0.00	0.15±0.21	-	-	-0.088
		Sup./Inf.	0.00±0.00	0.00±0.00	0.43±0.11	-	-	0.026
		Lat./Med.	0.00±0.00	0.00±0.00	-1.35±0.18	-	-	-

Note: Marker abbreviations are explained in Table 1. The replacement direction (repl. direc.) is in anterior/posterior (Ant./Post.), superior/inferior (Sup./Inf) and Lat./Med.) direction, of which the first is in positive direction.
Color coding: linear distribution from zero (white) to absolute highest (red or blue) value of both models as in the following: and

direction (-0.088°/mm/cm).

4. Discussion

This study was the first to comprehensively quantify the marker placement sensitivity of multi-segment foot kinematics of all anatomical markers used in OFM and RFM. The main finding was that for every foot segment of both models at least one marker demonstrated a placement sensitivity of 1.0°/mm or more. These included the markers at the posterior aspect of the calcaneus (1.5°/mm) and in between the base and head of the 2nd and 3rd metatarsal (1.4°/mm). In addition, it was shown that foot size had a small but significant effect (≤0.10°/mm/cm) on 40% of the sensitivity values.

The marker sensitivity values are inherent to the definitions of OFM and RFM (Leardini et al., 2007; Schallig et al., 2020; Stebbins et al., 2006). Misplacement of single markers that directly define the direction of an axis of a SCS (e.g. the origin), have the largest effect on the segment orientation. In OFM, the distal heel marker (HEE) is the origin of the hindfoot SCS and used to define several axes, hence it has a high placement sensitivity causing errors in all planes, but mainly the transverse plane (1.4°/mm) and together with the CALP marker in the frontal plane (1.4 and 1.5°/mm). Others also found that the kinematics are sensitive to misplacement of this marker (Carty et al., 2015; Paik et al., 2014), with even higher sensitivity values of 4°/mm (Paik et al., 2014). Next to the markers on the posterior aspect of the calcaneus, misplacement of the marker at the base of the 5th metatarsal also causes an error in the sagittal plane of the hindfoot, as found by others as well (Carty et al., 2015). This is a result of the use of the marker at the base of the 5th metatarsal to determine the anterior-posterior axis. The forefoot SCS of OFM is defined by using a plane defined by HM1M, HM5 and BM5, hence this plane is sensitive to misplacement of these markers. In addition, the anterior-posterior axis is pointing towards the HM23 marker and is therefore sensitive to medio-lateral misplacement of the HM23 marker.

To our knowledge, this study is the first to quantify the marker placement sensitivity within RFM. In RFM, the CALP marker is the origin of the hindfoot SCS and used to define the direction of the anterior axis. Misplacement of this marker is causing mainly errors in the sagittal and transverse plane, but smaller than the misplacement of the origin of OFM (1.0 vs. 1.5°/mm). In general, the forefoot orientation is more sensitive to marker misplacement in RFM compared to OFM. Mainly medio-lateral misplacement of the marker at the base of the 2nd metatarsal, which is the origin of the forefoot SCS, and the HM23 marker, which together are used to determine the anterior-posterior axis, are causing errors in the transverse plane. In this study, we used the HM23 marker instead of a marker at the 2nd metatarsal as actually prescribed by RFM. However, since the two marker locations are close together and the HM23 marker is used in the altered and the reference coordinate system, it is unlikely to affect the marker placement sensitivity values. For both models, largest marker placement sensitivity values were found in the frontal or transverse plane, likely because the anterior-posterior and vertical axes were directly defined by markers in the model definitions (Schallig et al., 2020).

The marker sensitivity values found in this study indicate that inconsistent marker placement is one of the factors in multi-segment foot models that cause clinically relevant errors. In gait analyses, an angular difference > 5° is generally considered as a clinically relevant difference (McGinley et al., 2009). The actual error in segment orientation is a combination between the marker placement sensitivity values and its actual misplacement. We found marker sensitivity values of ≥ 1.0°/mm for every foot segment. For markers on the hindfoot, manual placement variability up to 6 mm between testers have been reported (Deschamps et al., 2014). Hence, misplacements in this order of magnitude will cause segment orientation errors > 5°, which are considered as clinically relevant. For midfoot and forefoot markers, mean differences between observers of 3.2–4.6 mm have been found, with one exception for the marker on the 2nd metatarsal head which had a mean difference of 13.1 mm (Bishop et al., 2013). However, this was probably a result of the inconsistent placement of the inexperienced tester, who also had a much higher intra-rater mean difference compared to the experienced tester (7.9 mm vs. 3.5 mm) (Bishop et al., 2013). Nevertheless, the marker on the 2nd metatarsal head is apparently a marker that is susceptible for marker misplacement, while it also showed a high sensitivity in this study. Combining the sensitivity values of the forefoot markers with the actual misplacements again results in segment orientation errors which are considered clinically relevant. However, it is important to mention that the clinically relevant difference of > 5°, is based on general lower extremity kinematics (McGinley et al., 2009). A similar review is needed to determine the clinical relevant differences for multi-segment foot kinematics.

Some methodological assumptions were made in the setup of this study that need some additional explanation for a proper interpretation of the data. First, virtual marker replacements were performed in a static standing trial instead of during gait trials. This is in contrast with for example Carty et al. (2015), who determined the marker placement sensitivity during gait with a standard misplacement in four directions. However, with the current setup the effect of solely marker misplacement could be determined without other factors interfering like for example soft tissue artifacts (Schallig et al., 2021). Moreover, the errors in the dynamic trials will mainly be an offset equal to the values found in the static trials, because the virtual marker misplacements only have an effect on the anatomical coordinate system orientation. Second, the markers on the feet of the children and adults were placed by different testers, which is obviously suboptimal. However, both testers had sufficient training and any inconsistencies in marker placement would only affect the reference coordinate system, since the replacements were performed virtually. Third, we made the assumption that the relation between marker misplacement in mm and segment orientation error in degrees (i.e. marker sensitivity) was linear (Fig. 2A). After visually inspecting the data, this appeared to be the case for almost all markers, as also shown by the $R^2 > 0.99$ in 89% of the linear fits. However, in a few exceptions a non-linear relation seemed to be present. Hence, mainly with extreme misplacements (>10 mm) the sensitivity value should be interpreted with caution. Third, in practice, not all markers can be misplaced in three directions as done in the current study setup. For example, the markers on the medial and lateral side of the calcaneus can be misplaced in anterior-posterior and superior-inferior direction, but when misplaced in medio-lateral direction the markers will not be on the skin anymore. The same applies to markers on the forefoot which are most likely misplaced in medio-lateral and anterior-posterior direction. However, when misplaced in anterior-posterior direction these markers will also move slightly superior-inferiorly due to the foot arch.

Clinically, joint angles (i.e. the rotation between two segments) instead of segment orientations are used as output of the foot models. In this study, we provided the marker sensitivity of the segment orientations to show the effect of marker misplacement on each segment separately, without being influenced by the decomposition order when obtaining joint angles. The decomposition of the rotation matrix of a joint (between two segments) is not linear, which means that the marker sensitivity of the segment orientations is not necessarily exactly the same as the one based on joint angles. In an additional analysis we compared the difference in sensitivity between segment orientations and the corresponding joint angles as a consequence of the same single marker misplacement. In general, differences were very small (96.5% was ≤ 0.1°/mm), with some exceptions (max: 0.4°/mm) for marker sensitivity values of RFM. These exceptions were already close to zero °/mm and mainly present in the transverse plane, likely as a consequence of the decomposition order, in which the third rotation takes place in the transverse plane. The differences for markers with relatively large sensitivity values (≥±0.5°/mm) were all < 0.2°/mm. Therefore, determining the marker sensitivity based on either the segment orientations or joint angles does not affect the conclusions of this study.

As some errors due to inconsistent marker misplacement were found to be substantial and clinically relevant, it is important to reduce those errors. Multiple devices have been developed that improve marker placement consistency (Deschamps et al., 2014; Kalkum et al., 2016; McCahill et al., 2021; Simon et al., 2006; Telfer et al., 2010). Some are used for all markers on the foot (Kalkum et al., 2016; Telfer et al., 2010), while others focus on the heel marker (McCahill et al., 2021) or the medial and lateral makers on the calcaneus (Deschamps et al., 2014; Simon et al., 2006). The latter is remarkable, because our results and those of others (Carty et al., 2015; Paik et al., 2014) show that errors in the hindfoot segment orientation are mainly caused by inconsistent marker misplacement of the markers at the posterior aspect of the calcaneus and not on the ones on the medial and lateral sides. Other multi-segment foot models, like the Milwaukee foot model (Kidder et al., 1996) and mSHCG foot model (Saraswat et al., 2012), have the option to use weight bearing radiographic measures to correct their marker-based coordinate systems, which aligns them to the underlying bony anatomy. This will likely reduce the errors due to anatomical marker misplacements. However, this method introduces the potential error of quantifying radiographic measures in 2D for 3D bone structures. The last possible solution we suggest to reduce the errors, is to reconsider the role of the markers with a high sensitivity within the models' definitions. Segment orientations are mainly sensitive to the misplacement of markers that are used as origin in a SCS (e.g. CALP and BM2 in RFM and HEE in OFM) or single markers that are used to determine the direction of an axis (e.g. HM23 for the anterior-posterior axis in both models). This can be improved by for example taking the midpoint between two markers, which roughly halves the error.

5. Conclusion

This study identified anatomical marker locations used in OFM and RFM for which consistent marker placement is most critical to obtain repeatable foot kinematics. Highest marker sensitivity values were found for markers that solely define the direction of an axis of a segment coordinate system (e.g. as the origin), like the marker at the posterior aspect of the calcaneus in OFM and the basis of the second metatarsal in RFM. The role of these markers within the models' definitions need to be reconsidered to reduce errors and improve repeatability.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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