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DOI
10.1016/j.gaitpost.2020.08.126

Publication date
2020

Document Version
Final published version

Published in
Gait and Posture

Gait & Posture 82 (2020) 126–132

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Comparing the kinematic output of the Oxford and Rizzoli Foot Models during normal gait and voluntary pathological gait in healthy adults

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ARTICLE INFO

Keywords:
Foot kinematics
Multi-segment foot models
Gait analysis
Biomechanics
Statistical parametric mapping

ABSTRACT

Background: The Oxford Foot Model (OFM) and Rizzoli Foot Model (RFM) are the two most frequently used multi-segment models to measure foot kinematics. However, a comprehensive comparison of the kinematic output of these models is lacking.
Research question: What are the differences in kinematic output between OFM and RFM during normal gait and typical pathological gait patterns in healthy adults?.
Methods: A combined OFM and RFM marker set was placed on the right foot of ten healthy subjects. A static standing trial and six level walking trials were collected for normal gait and for four voluntarily adopted gait types: equinus, crouch, toe-in and toe-out. Joint angles were calculated for every trial for the hindfoot relative to shank (HF-SH), forefoot relative to hindfoot (FF-HF) and hallux relative to forefoot (HX-FF). Average static joint angles of both models were compared between models. After subtracting these offsets, the remaining dynamic angles were compared using statistical parametric mapping repeated measures ANOVAs and *t*-tests. Furthermore, range of motion was compared between models for every angle.
Results: For the static posture, RFM compared to OFM measured more plantar flexion ($\Delta = 6^{\circ}$) and internal rotation ($\Delta = 7^{\circ}$) for HF-SH, more plantar flexion ($\Delta = 34^{\circ}$) and inversion ($\Delta = 13^{\circ}$) for FF-HF and more dorsal flexion ($\Delta = 37^{\circ}$) and abduction ($\Delta = 12^{\circ}$) for HX-FF. During normal walking, kinematic differences were found in various parts of the gait cycle. Moreover, range of motion was larger in the HF-SH for OFM and in FF-HF and HX-FF for RFM. The differences between models were not the same for all gait types. Equinus and toe-out gait demonstrated most pronounced differences.
Significance: Differences are present in kinematic output between OFM and RFM, which also depend on gait type. Therefore, kinematic output of foot and ankle studies should be interpreted with careful consideration of the multi-segment foot model used.

1. Introduction

Measuring foot kinematics during gait is of particular interest in patients where static and/or dynamic foot deformities are present. These include neuromuscular (e.g. cerebral palsy) and musculoskeletal (e.g. rheumatoid arthritis) disorders that affect the foot and ankle. Traditionally in gait analysis, the foot has been modeled as one rigid segment, but more recently, many multi-segment foot models have been developed to capture foot kinematics in more detail [1–3]. It has been shown that a one-segment foot model provides different and sometimes even contradictory results compared to a multi-segment foot model [4]. Hence, to represent the complexity of the foot, multi-segment foot models are preferred. Among the proposed multi-segment foot models, the Oxford Foot Model (OFM) [5] and the Rizzoli Foot Model (RFM) [6,

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https://doi.org/10.1016/j.gaitpost.2020.08.126
Received 14 February 2020; Received in revised form 23 August 2020; Accepted 24 August 2020
Available online 28 August 2020

7] have been used most frequently both clinically and in research [1,3]. Insight into the differences between these two models will be useful when deciding to use one of these two models or when comparing results of studies using either model.

OFM and RFM have been compared directly in a number of studies [8–11]. In terms of repeatability, the kinematics measured in young healthy adults were found to be more reproducible and repeatable (both within and between subjects) for RFM than OFM, as shown by the intra-class correlation coefficients and standard errors [8]. However in pediatric foot motion similar repeatability and test-retest errors were found for both models [9]. The actual kinematic output of both models from the same data collection has, to our knowledge, never been thoroughly compared. One study did compare the kinematic output of the two models from simultaneous acquisitions [10], but they placed the medial and lateral calcaneus markers with a heel alignment device instead of directly on the sustentaculum tali and peroneal tubercle as described in the RFM definitions [6,7]. Moreover, this study was performed in healthy gait only. However, gait analyses are mainly performed in a clinical setting and the differences between the models could be affected by the gait type. Hence, it is relevant to compare the foot models in normal as well as in pathological gait types such as equinus, crouch, toe-in and toe-out gait, which are common gait abnormalities in cerebral palsy [12].

Therefore, the aim of this study is to compare the kinematic output of OFM and RFM during normal gait and to determine whether differences between models are consistent for a range of pathological gait patterns as adopted by healthy volunteers. Differences in kinematic output are expected between OFM and RFM because of the different marker locations and segment axes definitions. Mainly static offsets are expected, which will also affect the kinematic output during the gait trials.

2. Methods

2.1. Participants

Ten healthy subjects (6 female, age:26.8 ± 2.6 years, height:176.4 ± 8.1 mm, weight:67.2 ± 8.5 kg) with a normal foot posture index (2.4 ± 1.4) [13] were recruited for this study. Subjects did not wear insoles, nor had foot or ankle complaints in the last year nor any disorders that could affect the gait pattern. Informed consent was signed by all subjects and ethical approval was provided by the local ethics committee.

2.2. Data collection

Subjects underwent three-dimensional gait analysis. Passive retro-reflective markers (ø12.7 mm) were placed on both lower extremities according to the Newington-Helen Hayes marker model [14,15]. On the right foot, additional markers (ø9.5 mm) were placed according to OFM [5] and RFM [6,7] definitions. In total, 22 markers were placed on the tibia and foot (Table 1). The RFM marker on the head of the 2nd metatarsal was replaced by the OFM marker between the 2nd and 3rd metatarsal head, following Mahaffey et al. [9], because of the close proximity of these two markers.

First a static standing trial was performed to calculate the static angles. Next, subjects walked barefoot at a self-selected walking speed on a 10 m walkway. Six trials were collected for normal gait, as well as for voluntarily adopted equinus (i.e. toe-walking), crouch (i.e. with flexed knees and complete foot contact), toe-in and toe-out gait (i.e. internal/external foot progression). During all trials, marker trajectories were recorded by a 12-camera motion capture system (Vicon Motion Systems Ltd., Oxford, UK). Five force plates (AMTI, Watertown, USA) were used to determine gait events.

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 *(wand marker)*	CPEG	x	
	7	Posterior aspect calcaneus proximal	PCA	x	x
	8	Posterior aspect calcaneus distal	HEE	x	x
	9	Medial calcaneus	MCAL	x	
	10	Lateral calcaneus	LCAL	x	
	11	Peroneal tubercle	PTU		x
	12	Sustentaculum tali	STL		x
Midfoot	13	Medial apex tuberosity of navicular	NAV		x#
Forefoot	14	Base metatarsal 1	BM1	x	x
	15	Head metatarsal 1	HM1		x
	16	Head metatarsal 1 medial	HM1M	x	
	17	Head metatarsal 5	HM5	x	x
	18	Base metatarsal 5	BM5	x	x
	19	Halfway between 2nd and 3rd metatarsal head	TOE	x	x*
	20	Halfway between 2nd and 3rd metatarsal base	BM2		x*
Hallux	21	Head of proximal phalanx of hallux medial	HLX	x	
	22	Head of proximal phalanx of hallux dorsal	BHLX		x

Not used in the calculations for this study.
* 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.

2.3. Data analysis

Output of OFM was calculated by its implementation in the Vicon Nexus (v2.6.1) pipeline, in which the hindfoot flat option (Appendix A) was not checked. Output of RFM was calculated by custom-made scripts in Matlab (R2017b, MathWorks, USA), according to the definitions published [6,7]. Joint kinematics were calculated for every trial for hindfoot relative to shank (HF-SH), forefoot relative to hindfoot (FF-HF) and hallux relative to forefoot (HX-FF). Joint angles in both models were calculated according to Grood and Suntay [16]. Note that the longitudinal axis of the hindfoot and forefoot segment, around which the third rotation takes place, is defined as the anterior axis in OFM and as the vertical axis in RFM (Appendix A). Trials were time-normalized to 100 % of the gait cycle. Initial contacts were determined by force plate data, if successful hits were unavailable the foot velocity [17] was used. For each gait type, from the six collected trials, three successful ones were randomly selected per subject, by using the default random number generator in Matlab, and their output was averaged.

Static differences between the models were determined by calculating the joint angles during the standing trial. For each subject, the dynamic differences between the models were obtained after subtracting the static angles (offset) from the corresponding joint angles from the walking trials, which allowed for a better separate comparison of the dynamic differences between the models. In addition, range of motion

(ROM) was calculated for every joint angle during each gait type, by taking the difference between the maximum and minimum value over each gait cycle.

2.4. Statistical analysis

The static joint angles of both models were compared with paired-sample *t*-tests. 1D Statistical parametric mapping (SPM), performed in Matlab, was used to compare the dynamic joint angles over time [18]. First, joint angles of the normal walking trials were compared with SPM paired-sample *t*-tests. Second, to analyze the effect of gait type, joint angles during normal gait and the voluntary pathological gait types were compared with SPM repeated-measures ANOVAs with foot model and gait type as factors (main and interaction effects calculated). When significant, corresponding post-hoc tests with Bonferroni corrections were performed. The same statistical tests were performed for the ROM values of the different walking types, by using IBM SPSS statistics (version 24, SPSS INC., Chicago, IL, USA). Significance level was set at α=0.05.

3. Results

Static joint angle differences were found between OFM and RFM (Table 2). For RFM compared to OFM, hindfoot relative to shank (HF-SH) was on average in more plantar flexion ($\Delta = 6°$) and internal rotation ($\Delta = 7°$). Furthermore, for forefoot relative to hindfoot (FF-HF), RFM measured on average more plantar flexion ($\Delta = 34°$) and inversion ($\Delta = 13°$) than OFM. For hallux relative to forefoot (HX-FF), RFM measured dorsal flexion and abduction, while OFM measured plantar flexion and adduction, resulting in a difference of 37° and 12° respectively.

During normal walking, the corrected dynamic joint angles of OFM showed more HF-SH plantar flexion during the loading response and dorsal flexion at the terminal stance phase compared to RFM (Fig. 1). This was also reflected in the ROM (Table 3), which was on average 4° larger for OFM. In addition, OFM measured more external rotation at the beginning of the stance and swing phase, which resulted in a 10° larger ROM. In contrast, for FF-HF, RFM measured on average 12° more plantar flexion in the late stance and early swing phases, more abduction during mid-stance and more adduction during the pre-swing (6° larger ROM). Moreover, for HX-FF, RFM measured about 18° more dorsal flexion and 9° more adduction in the period around push-off.

Table 2
Static joint angles calculated for OFM and RFM and their absolute difference. P-values are bold when OFM and RFM are significantly different.

Joint	Plane	OFM (°)	RFM (°)	p-value	Absolute difference (°)
HF-SH	Sagittal: DF(+)/PF (-)	−0.9 ± 5.4	−4.7 ± 7.1	***0.023***	5.8 ± 4.4
	Frontal: Inv(+)/Ev (-)	−1.3 ± 3.7	0.8 ± 3.6	0.371	2.1 ± 7.1
	Transverse: IntRot (+)/ExtRot(-)	8.3 ± 8.3	15.6 ± 4.9	***0.029***	7.3 ± 8.9
FF-HF	Sagittal: DF(+)/PF (-)	1.4 ± 3.5	−32.0 ± 9.2	***<0.001***	33.5 ± 9.9
	Frontal: Inv(+)/Ev (-)	4.6 ± 2.0	17.9 ± 5.4	***<0.001***	13.4 ± 6.4
	Transverse: Add (+)/Abd(-)	−1.2 ± 5.5	3.0 ± 5.9	0.180	4.2 ± 9.1
HX-FF	Sagittal: DF(+)/PF (-)	−8.4 ± 5.8	28.6 ± 10.5	***<0.001***	37.0 ± 12.9
	Transverse: Add (+)/Abd(-)	2.0 ± 5.4	−10.1 ± 8.1	***<0.01***	12.1 ± 11.3

Abbreviations: HF-SH: Hindfoot relative to Shank, FF-HF: Forefoot relative to Hindfoot, HX-FF: Hallux relative to Forefoot; DF: dorsal flexion, PF: plantar flexion, Inv: Inversion, Ev: Eversion, IntRot: Internal Rotation, ExtRot: External Rotation, Add: Adduction, Abd: Abduction.

For equinus and crouch gait, only the sagittal plane angles are presented, since the models were challenged in that plane by these gait types (Fig. 2 and Table 3). The angles in the other planes are presented in Appendix B. A significant interaction effect between gait type and foot model was found for HF-SH (for 1–22 % and 35–99 % of the gait cycle), FF-HF (for 0–2 %, 15–58 %, 85–100 % of the gait cycle) and HX-FF (for 3–60 % and 87–96 % of the gait cycle). Subsequent post-hoc analysis showed that for HF-SH in equinus gait, OFM was in more plantar flexion than RFM during the swing phase, although the ROM was not different. Contrarily, in crouch gait no differences between dynamic joint angles were found, but the ROM was different. For both FF-HF and HX-FF a larger part of the gait cycle was significantly different between models for equinus compared to normal and crouch gait. For all gait types RFM measured a larger ROM compared to OFM.

For toe-in and toe-out gait, only the transverse plane angles are presented, since the models were challenged in that plane by these gait types (Fig. 3 and Table 3). The angles in the other planes are presented in Appendix B. A significant interaction effect between gait type and foot model was found for HF-SH (for 0–100 % for of the gait cycle) and for FF-HF (for 6–33 % and 50–83 % of the gait cycle) and HX-FF (3–25 %, 27–34 %, 49–59 % and 81–85 % of the gait cycle). Subsequent post-hoc analysis showed that for HF-SH, a smaller part of the gait cycle was significantly different for toe-in gait and a larger part during toe-out gait compared to normal. OFM measured a larger ROM for all gait types. For FF-HF and HX-FF a significant difference was found between the models during mid-stance for normal walking and toe-out gait but not for toe-in gait. For all gait types RFM measured a larger ROM for FF-HF and HX-FF.

4. Discussion

The aim of this study was to compare the kinematic outputs of two state-of-the-art multi-segment foot models (i.e. OFM and RFM) during normal gait and voluntarily adopted pathological gait types. The main finding of this study was that significant and relevant differences in both static and dynamics joint angles are present between OFM and RFM, and moreover that these differences depend on the gait type. Differences between the models were more pronounced during gait types in which the foot is more plantar flexed or externally rotated (i.e. equinus or toe-out gait) and less pronounced when the foot is more dorsal flexed or internally rotated (i.e. crouch or toe-in gait) compared to normal gait.

Static differences were found between the two models, likely because OFM and RFM use different marker sets and anatomical axes definitions, which results in different segment reference frames and consequently joint angles (Appendix A). Moreover, the decomposition order of the coordinate frames is different between the two models. Both use the Grood and Suntay [16] joint convention, but the longitudinal axis (3^{rd} rotation) of the foot segments is defined anteriorly in OFM and vertically in RFM. In general, OFM aims to align its coordinate systems to the plantar surface, hence the static angles are around zero for healthy subjects. In contrast, RFM aims to align the segment coordinate systems to the bony structures, which results in larger static angles [7]. An example of these different approaches is the forefoot, for which the largest differences in static joint angles were found. In both models the anterior axis of the forefoot is defined towards the heads of the middle metatarsals, but the origin is different. OFM uses a projection on the plantar surface, while RFM uses the base of the 2^{nd} metatarsal, which is further away from the plantar surface, resulting in a more plantar flexed orientation of the forefoot and FF-HF joint angle. Furthermore, in the frontal plane, FF-HF of RFM is more inverted than OFM. This is probably caused by the marker on the first metatarsal head, which is placed on the medial aspect for OFM and on the dorsal aspect for RFM. The relatively higher position with respect to the marker on the 5^{th} metatarsal head, results in more inversion for RFM. No static differences were found in the transverse plane of FF-HF, but it should be mentioned that in the present study the marker in between the heads of the 2^{nd} and 3^{rd} metatarsal was used for both models. However, RFM definitions actually

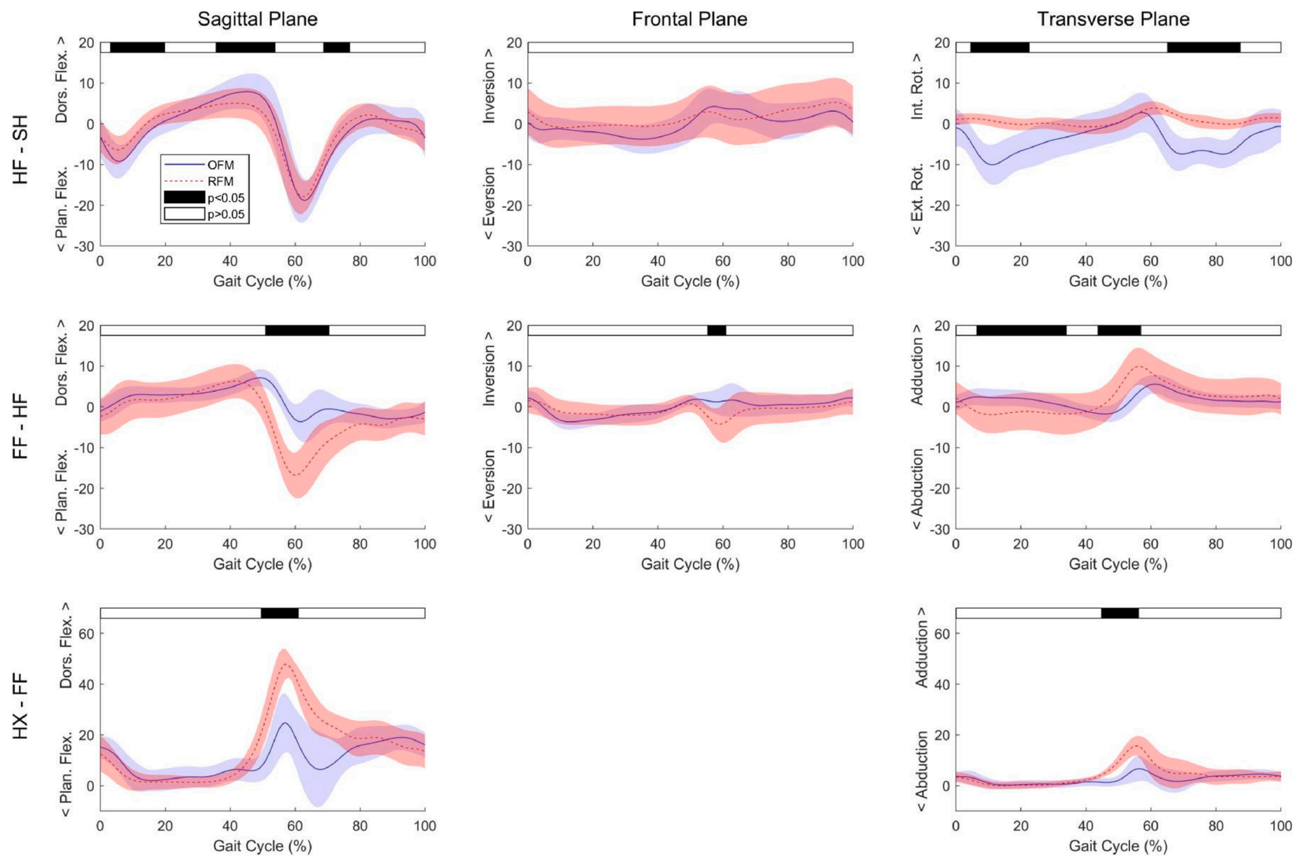

Fig. 1. Joint angles calculated for OFM (solid blue) and RFM (dashed red) during normal walking: mean and standard deviation (colored band) are shown. Black box shows the part of the gait cycle in which a significant difference is present ($p < 0.05$) between the models according to SPM.

Table 3
Range of motion of the joint angles during normal walking, equinus, crouch, toe-in and toe-out gait calculated for OFM and RFM and their absolute and relative difference. P-values are bold when OFM and RFM are significantly different.

Joint	Gait Type	Plane	OFM (°)	RFM (°)	p-value	Absolute difference (°)	Relative difference (% of mean OFM and RFM ROM)
HF-SH	Normal	Sagittal: DF(+)/PF(-)	27.4 ± 3.3	23.8 ± 3.0	**<0.001**	3.6 ± 1.1	14.0 ± 4.1
		Frontal: Inv(+)/Ev(-)	10.0 ± 1.9	7.0 ± 1.4	**<0.01**	3.0 ± 2.0	35.0 ± 21.6
		Transverse: IntRot(+)/ExtRot (-)	15.1 ± 4.2	5.1 ± 1.7	**<0.001**	10.0 ± 3.8	98.5 ± 24.9
	Equinus	Sagittal: DF(+)/PF(-)	23.7 ± 3.6	23.6 ± 3.4	0.48	0.5 ± 2.0	7.0 ± 4.9
	Crouch	Sagittal: DF(+)/PF(-)	25.1 ± 2.2	22.5 ± 2.7	**<0.01**	2.7 ± 2.1	12.5 ± 7.4
	Toe-in	Transverse: IntRot(+)/ExtRot (-)	15.3 ± 5.4	7.8 ± 2.3	**<0.01**	7.5 ± 5.1	60.7 ± 35.5
	Toe-out	Transverse: IntRot(+)/ExtRot (-)	11.3 ± 3.6	4.1 ± 1.0	**<0.001**	7.2 ± 3.7	89.8 ± 28.7
FF-HF	Normal	Sagittal: DF(+)/PF(-)	12.5 ± 3.5	24.3 ± 3.7	**<0.001**	11.8 ± 5.0	65.6 ± 28.2
		Frontal: Inv(+)/Ev(-)	8.6 ± 2.2	7.7 ± 1.7	0.21	0.9 ± 2.2	25.7 ± 13.4
		Transverse: Add(+)/Abd(-)	8.1 ± 1.9	13.7 ± 3.8	**<0.001**	5.6 ± 3.5	49.3 ± 27.8
	Equinus	Sagittal: DF(+)/PF(-)	13.8 ± 3.8	22.1 ± 4.5	**<0.001**	8.3 ± 4.5	46.7 ± 24.5
	Crouch	Sagittal: DF(+)/PF(-)	11.9 ± 2.7	22.3 ± 2.8	**<0.001**	10.4 ± 4.4	61.0 ± 25.8
	Toe-in	Transverse: Add(+)/Abd(-)	9.0 ± 2.7	16.1 ± 3.4	**<0.001**	7.1 ± 3.7	56.0 ± 26.6
	Toe-out	Transverse: Add(+)/Abd(-)	5.1 ± 1.7	8.9 ± 3.2	**<0.01**	3.7 ± 3.3	54.0 ± 35.6
HX-FF	Normal	Sagittal: DF(+)/PF(-)	31.2 ± 9.0	49.4 ± 3.4	**<0.001**	18.2 ± 8.7	47.7 ± 25.3
		Transverse: Add(+)/Abd(-)	8.6 ± 4.0	18.0 ± 4.7	**<0.001**	9.4 ± 5.8	34.0 ± 6.8
	Equinus	Sagittal: DF(+)/PF(-)	30.6 ± 5.9	51.4 ± 6.5	**<0.001**	20.8 ± 7.2	51.2 ± 17.5
	Crouch	Sagittal: DF(+)/PF(-)	27.3 ± 10.8	43.9 ± 4.6	**<0.01**	16.6 ± 11.4	53.5 ± 28.8
	Toe-in	Transverse: Add(+)/Abd(-)	6.0 ± 3.6	13.7 ± 6.1	**<0.01**	7.6 ± 5.3	59.9 ± 34.8
	Toe-out	Transverse: Add(+)/Abd(-)	7.0 ± 4.3	12.1 ± 3.2	**<0.01**	5.0 ± 4.7	66.3 ± 31.8

Abbreviations like in Table 2.

prescribe a marker on the head of the 2nd metatarsal, as also adopted by Mahaffey et al. [9], because of the close proximity of these two markers. This likely resulted in a slightly externally rotated FF-HF of the present RFM compared to its conventional definitions. In addition, it should be noted that RFM also tracks the midfoot. Hence, FF-HF can be split into separate Chopart and Lisfranc joints, which can be useful information for some foot pathologies [19].

During normal walking, dynamic differences between the models were found in specific parts of the gait cycle and in ROM. The kinematic output was similar in terms of general pattern and ROM to literature for

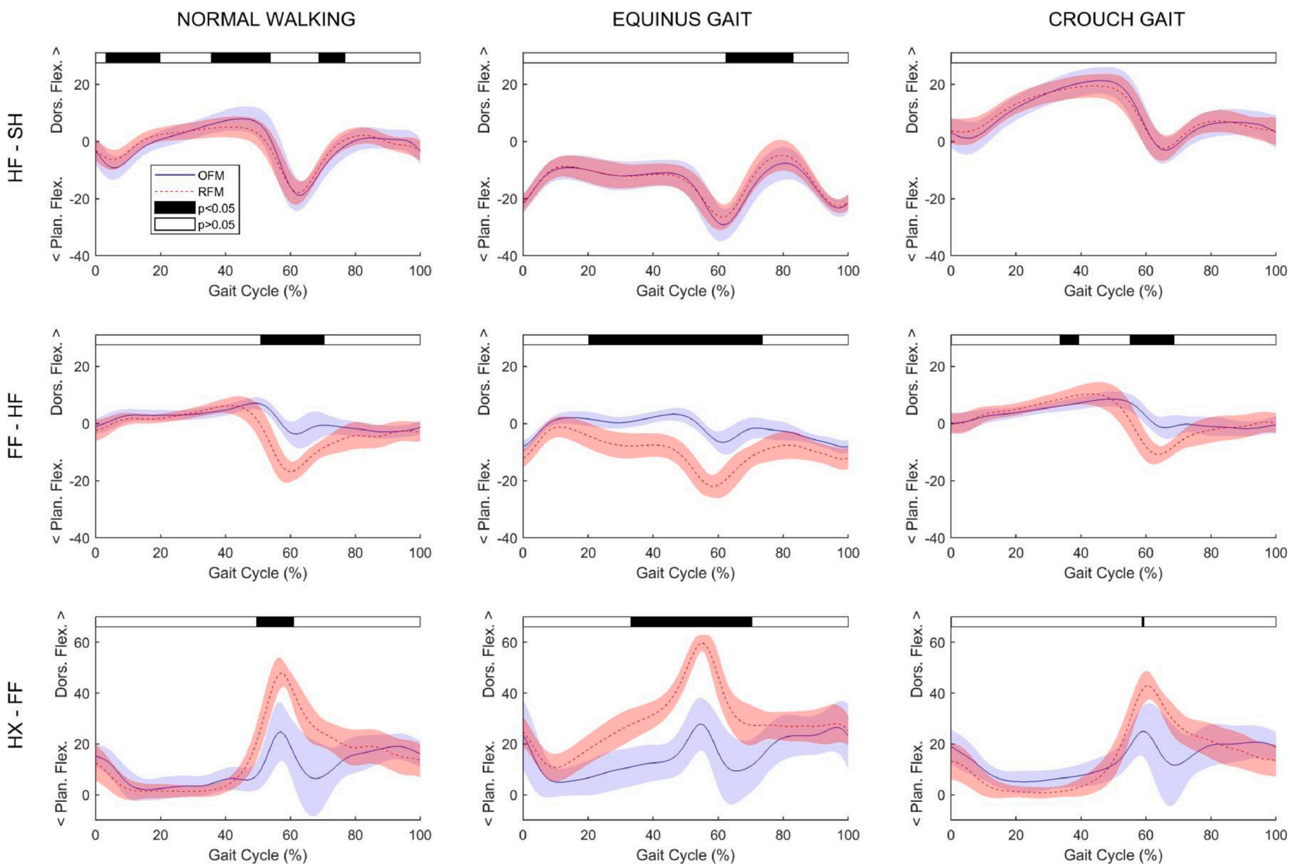

Fig. 2. Sagittal plane joint angles calculated for OFM (solid blue) and RFM (dashed red) during normal walking, equinus and crouch gait: mean and standard deviation (colored band) are shown. Black box shows the part of the gait cycle in which a significant difference is present ($p < 0.05$) between the models according to SPM.

both OFM [5,20,21] and RFM [6,7,22]; only OFM ROM in the transverse plane of SH-HF was about 5° larger in this study compared to previous reports [5,20,21]. During normal walking, the ROM in the sagittal plane of HF-SH was slightly larger for OFM (27.4°) than RFM (23.8°). However, a bone pin study measured a ROM of 17.0° between the calcaneus and tibia in the sagittal plane [23], which suggests that both models may overestimate this rotation. In contrast to HF-SH, the ROM of FF-HF was larger in RFM (24.3°) compared to OFM (12.5°). The same bone pin study reported 17.6° between the talus and the 1st metatarsal. In the frontal plane, ROM of HF-SH as measured by OFM (10.0°) was closer to the bone pin value (11.3°) than RFM (7.0°). On the other hand, ROM of respectively HF-SH and FF-HF in the transverse plane as measured by RFM (5.1° and 13.7°) were closer to corresponding values obtained with bone pins (7.3° and 14.7°) than OFM (15.1° and 8.1°). Comparing the models output to data from a bone pin study provides insight into its validity. However, it is important to realize that the values in the bone pin study were determined only over the stance phase and only from six subjects.

The significant interaction effects between the factors model and gait pattern indicate that the models respond differently to the pathological gait patterns. The kinematic output of the models in the sagittal plane was different for a larger part of the gait cycle when walking in equinus gait, but smaller when walking in crouch, compared to normal walking. In the transverse plane, a larger part of the gait cycle was different between models for walking in toe-out gait, but smaller for toe-in gait. It seems that RFM did not distinguish between normal walking, toe-in and toe-out gait, while OFM did measure more internal/external rotation during toe-in/toe-out gait in HF-SH. However, it is not clear whether the toe-in and toe-out gait as adopted in this study actually originated from the ankle joint, since voluntary modifications of the foot progression angle can also originate from the hip and knee joints [24]. In the frontal plane barely any differences were present in the dynamic trials. However, we did not challenge the models in this plane as we did with the sagittal and transverse planes.

The dynamic differences between the models could be caused by the different decomposition order, crosstalk and/or soft tissue artefacts. The different marker sets and axes definitions result in different coordinate systems for the segments as became evident from the static differences. This likely results in a different distribution of the 3D joint rotations across the anatomical planes (sometimes referred to as crosstalk). However, OFM measured more motion in HF-SH for all planes, as did RFM for FF-HF, which clearly indicates that other factors play a role. One of these factors could be soft tissue artefacts [25]. OFM and RFM use different marker positions, with likely different artefacts. Differences in kinematic output between OFM and RFM became larger when the foot was in more extreme positions (e.g. equinus gait), which points towards effects of soft tissue artefacts. These artefacts have been studied for the foot and ankle [26–28], however, their specific effect in OFM and RFM is unknown.

In this study the Vicon Nexus pipeline was used to calculate the multi-segment foot kinematics according to OFM, because this pipeline is largely used in clinical practice and in many research studies. However, the way OFM is coded in the Nexus software is not open source. Therefore we compared the output of the Nexus pipeline to the output of a custom-made Matlab code based the OFM definitions as described in literature [5] and found that the output is slightly different (Appendix C). Unfortunately, this shows that different versions of OFM exist and might be used in practice. Hence, it is important that authors of multi-segment foot modeling clearly state which OFM code they use.

Our results show that studies using different foot models should not be compared without careful consideration of how the models compare.

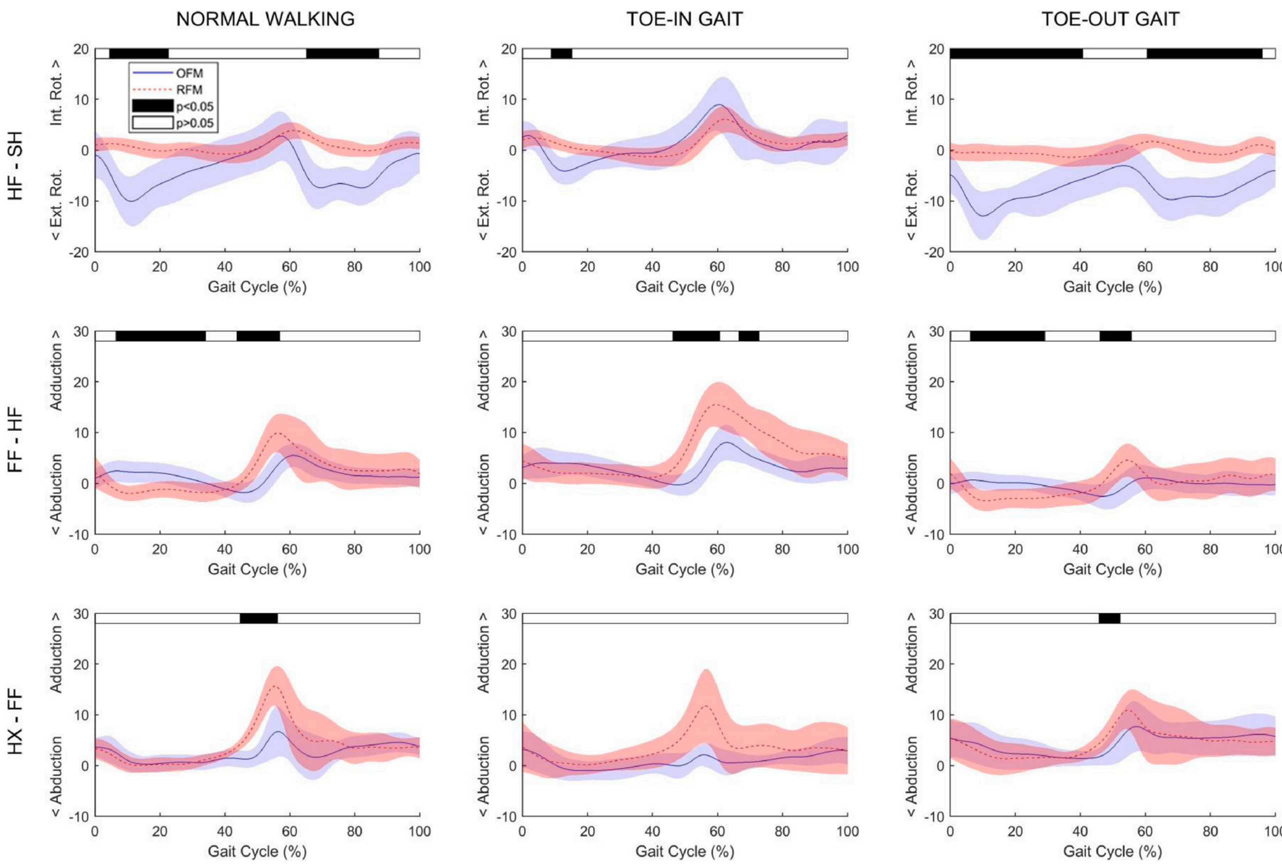

Fig. 3. Transverse plane joint angles calculated for OFM (solid blue) and RFM (dashed red) during normal walking, toe-in and toe-out gait: mean and standard deviation (colored band) are shown. Black box shows the part of the gait cycle in which a significant difference is present ($p < 0.05$) between the models according to SPM.

The most obvious difference is an offset between OFM and RFM. However, this offset cannot be used to correct for the differences in kinematic output between the models, since also dynamic differences are present, even depending on the gait type. Although the pathological gait types were simulated by healthy volunteers, the data shows that extra caution is warranted in gait types with more plantar flexion or external rotation, which are prevalent in clinical populations like cerebral palsy [12]. However, these results cannot be directly translated to a clinical population. Healthy subjects are never truly able to replicate pathological gait. For instance, because they do not have structural deformities, as also shown by their foot posture index. Hence, future studies should compare the kinematic output of these models in truly pathological gait. In addition, it is also important that future studies determine the sensitivity of both models in detecting kinematic alterations. This study is not able to provide a recommendation for one of the two models since it only showed the differences in kinematic output and not which models is more accurate. Future studies that use imaging techniques like computed tomography [29] or fluoroscopy [30] are needed to gain more insight into how the models output relate to the underlying bony kinematics.

5. Conclusions

Differences are present in both the static and dynamic output of OFM versus RFM. Moreover, these differences depend on the gait type and are present over a larger part of the gait cycle in gait types with more plantar flexion or external rotation. Therefore, kinematic output of foot and ankle studies should be interpreted with careful consideration of the multi-segment foot model used.

Funding

This research was supported by an internal grant of the Amsterdam Movement Sciences research institute.

Declaration of Competing Interest

The authors report no declarations of interest.

Acknowledgement

The authors would like to acknowledge Dr. Marian Harrington from the Oxford Gait Laboratory for her help with the Oxford Foot Model definitions and code.

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.2020.08.126.

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