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Review

Multi-segment foot models and their use in clinical populations

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ABSTRACT

Background: Many multi-segment foot models based on skin-markers have been proposed for in-vivo kinematic analysis of foot joints. It remains unclear whether these models have developed far enough to be useful in clinical populations. The present paper aims at reviewing these models, by discussing major methodological issues, and analyzing relevant clinical applications.
Research question: Can multi-segment foot models be used in clinical populations?
Methods: Pubmed and Google Scholar were used as the main search engines to perform an extensive literature search of papers reporting definition, validation or application studies of multi-segment foot models. The search keywords were the following: 'multisegment'; 'foot'; 'model'; 'kinematics', 'joints' and 'gait'.
Results: More than 100 papers published between 1991 and 2018 were identified and included in the review. These studies either described a technique or reported a clinical application of one of nearly 40 models which differed according to the number of segments, bony landmarks, marker set, definition of anatomical frames, and convention for calculation of joint rotations. Only a few of these models have undergone robust validation studies. Clinical application papers divided by type of assessment revealed that the large majority of studies were a cross-sectional comparison of a pathological group to a control population.
Significance: This review suggests that there is sufficient evidence that multi-segment foot models may be successfully applied in clinical populations. Analysis of the currently available models allows users to better identify the most suitable protocol for specific clinical applications. However new models require thorough validation and assessment before being used to support clinical decisions.

1. Introduction

In standard clinical gait analysis, three-dimensional (3D) motion of large body segments, such as the thorax, pelvis, thighs, and shanks, is analysed under the rigid-body assumption thus kinematics can be estimated from the trajectories of three non-aligned skin markers attached to palpable bony landmarks. The foot, however, is made up of 26 small bones and presents few accessible landmarks therefore markers attachment to bony landmarks can be challenging. Over the last three decades several methods have been proposed to improve the kinematic analysis of foot segments. These have recently been termed multi-segment foot models (MFMs). There remains considerable debate over how best to group foot bones into segments, particularly in specific, clinical contexts.

The value of multi-segment, rather than single-segment motion tracking has been demonstrated by observing kinematic alterations at foot joints other than the ankle, in both typically developing and clinical populations [1,2]. Significant differences have also been reported [3] when the multi-segment Oxford Foot Model (OFM, see Table 1) and the Plug-in-Gait (single-segment foot) model were used to characterize normal-arched and flat feet. The additional value of multi-segment foot analysis has also been demonstrated with respect to traditional identification of anatomical deformities in static conditions [4]. Measurements are affected by the complexity of multi-segment foot modeling and intrinsic errors from motion of the skin markers with respect to the underlying bone, the so-called soft tissue artifacts. However, the alternative techniques used in routine clinical analysis have significant limitations. Video fluoroscopy and bone pins provide more accurate measures of foot joint motion but are also invasive. Inertial sensors [5–7] and marker-less dynamic 3D scanning [8] are less invasive, but

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Table 1
List of published MFMs with details on the number of foot segments (shank always included), number of subjects used for validation, and name used for citation. The model name is indicated when it was recognized in the following literature or cited frequently in that way; some of these were taken from a previous review paper [9]. In bold those models with at least a clinical application reported in Table 2. In the last column, relevant papers of further assessment or validation are reported. Models and marker sets designed for bone pin analyses were excluded.

Authors	Year	Number of segments	population size	model name	validation papers
Kepple et al. [68]	1990	3	5		
Scott and Winter [69]	1991	3	3		
Moseley et al. [70]	1996	3	14		
Kidder et al. [71]	**1996**	**5**	**1**	**Milwaukee foot model**	Myers et al. [72], Long et al. [73], Long et al. [74]
Cornwall and McPoil [75]	1999	3	43	Cornwall I	Cornwall et al. [76] Cornwall et al. [77]
Woodburn et al. [78]	1999	3	10		
Rattanaprasert et al. [79]	**1999**	**5**	**10**	**Sydney foot model**	
Leardini et al. [80]	1999	6	9		
Wu et al. [81]	2000	3	10		
Hunt et al. [82]	2001	4	18		
Carson et al. [83]	**2001**	**5**	**1**	**Oxford Foot Model (OFM)**	Stebbins et al. [84], Curtis et al. [85], Wright et al. [86], van Hoeve et al. [87], Carty et al. [88], Lucarelli et al. [89], Milner and Brindle [90], Halstead et al. [91], McCahill et al. [62]
Arampatzis et al. [92]	2002	7	6		
MacWilliams et al. [15]	2003	10	18	Kinfoot	
Hwang et al. [18]	2004	10	5		
Davis et al. [93]	2006	3	1	Shriners Hospital for Children Greenville foot model (SHCG)	Maurer et al. (2013) [27]
Thomas et al. [56]	2006	3	39		
Pohl et al. [94]	2006	3	12		
Kitaoka et al. [95]	2006	4	20		
Simon et al. [96]	**2006**	**11**	**10**	**Heidelberg Foot Measurement Method (HFMM)**	Kalkum et al. [97]
Tome et al. [98]	2006	5	14		
Henley et al. [99]	2007	6	14		
Rao et al. [100]	**2007**	**4**	**10**	**Rao**	
Jenkyn and Nicol [101]	2007	6	12		Jenkyn et al. [102], Jenkyn et al. [103]
Leardini et al. [16]	**2007**	**5**	**10**	**Rizzoli Foot Model (RFM)**	Caravaggi et al. [63], Deschamps et al. [61,104], Arnold et al. [105], Portinaro et al. [17], Van den Herrewegen et al. [8]
Wolf et al. [40]	2008	4	6		
Sawacha et al. [29]	2009	4	10	Padua foot model	
Cobb et al. [20]	2009	4	11	Cobb foot model	
Tulchin et al. [106]	2010	3	20		
Hyslop et al. [107]	2010	6	9		
Oosterwaal et al. [22]	2011	26	25	Glasgow-Maastricht foot model	Oosterwaal et al. [23]
Bruening et al. [108]	2012	4	10		Bruening et al. [109]
De Mits et al. [110]	**2012**	**6**	**10**	**Ghent foot model**	
Saraswat et al. [111]	**2012**	**4**	**15**	**modified SHCG (mSHCG)**	Saraswat et al. 2013 [26]
Bishop et al. [112]	2013	4	18		
Chard et al. [113]	2013	4	13		
Nester et al. [114]	**2014**	**6**	**100**	**Salford foot model**	
Seo et al. [115]	2014	5	20		
Souza et al. [116]	2014	3	10		
Cobb et al. [21]	2016	7	10		

anatomical accuracy is compromised.

A number of review papers on multi-segment foot models (MFM) have been published. Rankine et al. [9] reported a systematic analysis of twenty-five papers, where models were classified in terms of number of bony segments and types of joint rotations. Deschamps et al. [10] showed that some foot joint rotation measures are still unreliable and observed that MFMs have yet to be used to address clinical problems. According to Bishop et al. [11] this is the consequence of poorly described or flawed methodologies, preventing readers from replicating the analysis in real clinical settings. To overcome these limitations and to provide common platforms for sharing and comparing foot kinematic data, they proposed a number of standards for reporting MFMs. The association between foot posture and lower limb kinematics has been addressed in a review by Bult et al. [12]. Novak et al. [13] highlighted the strengths and weaknesses of the most widely used MFMs. A thorough recent survey of the MFMs can be found also in Leardini et al. [14].

The last few decades have seen the emergence of many different MFMs, but little has yet been done to determine their clinical relevance in terms of treatment planning and quantification of outcomes. The present paper aims at reviewing available MFMs, discussing major methodological and technical issues, with a special focus on clinical applications. This knowledge should provide the basis for the selection of the most appropriate model from the currently available techniques, according to the specific population and study hypotheses, and highlight which clinical questions have directly benefitted from utilization of these MFMs.

2. Material and methods

From January to September 2018 PubMed and Google Scholar were searched for papers on kinematics of human foot segments in-vivo, i.e. any model that included more than one segment. The search included the key words “gait”, “foot”, “kinematics” and “segment” or “model” and involved all relevant previous review papers. The search was extended to all those papers cited in this initial series. All papers were

Table 2
Multi-segment foot models used in a clinical context. The column "age group" indicates whether the population analysed was Adults (A) or Children (C). The populations' age, if present in the paper, is reported as range (min-MAX), mean (SD), and/or as median (25 / 75 quartiles). Cumulative Controls/Patients age statistics are shown in italics. PTTD = Posterior tibial tendon dysfunction.

Reference	Year	Populations	Controls	Patients	age group	Application	Model	Summary of Outcome
Houck et al. [117]	2009	Stage II PTTD	n = 15 56.5 (7.7)	n = 30 59.8 (11.1)	A	1 Compare controls	HFMM	Differences found
Twomey et al. [118]	2010	Low arched feet	n = 25 11.1 (1.2)	n = 27 11.2 (1.2)	C	1 Compare controls	HFMM	Differences found
Canseco et al. [119]	2008	Hallux Rigidus	n = 25 52 (-)	n = 22 41 (-)	A	1 Compare controls	Milwaukee	Differences found
Canseco et al. [120]	2010	Hallux Valgus	n = 25 24-72	n = 33 27-73	A	1 Compare controls	Milwaukee	Differences found
Canseco et al. [121]	2017	Degenerative joint disease of the ankle	n = 36 18-27 23 (2.2)	n = 36 49-79 64 (7.0)	A	1 Compare controls	Milwaukee	Differences found (including other than the ankle)
Graf et al. [122]	2010	Clubfoot (post surgery)	n = 48 23.2 (2.4)	n = 24 21.8 (2.3)	A	1 Compare controls	Milwaukee	Similar kinematics
Khazzam et al. [123]	2006	Ankle arthritis	n = 25 27-73	n = 34 32-75	A	1 Compare controls	Milwaukee	Differences found
Khazzam et al. [124]	2007	Rheumatoid Arthritis	n = 25 27-73	n = 22 17-76	A	1 Compare controls	Milwaukee	Differences found
Ness et al. [125]	2008	PTTD	n = 25 41.3 (12.5)	n = 34 52.8 (9.5)	A	1 Compare controls	Milwaukee	Differences found
Maurer et al. [27]	2013	Mid-foot break	n = 15 7-15 10.1 (2.5)	n = 20 5-16 9.6 (3.3)	C	1 Compare controls	mSHCG	Differences found
Saraswat et al. [126]	2014	Planovalgus feet	n = 10 10.6 (1.6)	n = 10 10.6 (1.9)	C	1 Compare controls	mSHCG	Differences found
Alonso-Vazquez et al. [127]	2009	Forefoot Varus	n = 11 7-13	n = 10 8-13	C	1 Compare controls	OFM	Differences found but some disagreement with literature
Barton et al. [128]	2011	Patellofemoral pain syndrome	n = 20 23.4 (2.3)	n = 26 25.1 (4.6)	A	1 Compare controls	OFM	Differences found
Deschamps et al. [129]	2010	Hallux Valgus	n = 22 20-60	n = 20 18-65	A	1 Compare controls	OFM	Differences found
Levinger et al. [130]	2010	Flat foot	n = 10 24.3 (8.7)	n = 9 20.1 (1.3)	A	1 Compare controls	OFM	Differences found
Merker et al. [131]	2015	Juvenile idiopathic arthritis	n = 14 10.9 (9.9/ 12.6)	n = 11 11.7 (9.7/ 14.0)	C	1 Compare controls	OFM	Differences found
Mindler et al. [132]	2014	Clubfoot	n = 15 3-9	n = 32 3-8	C	1 Compare controls	OFM	Some small differences still present
Theologis et al. [133]	2003	Treated clubfoot	n = 15 7.7-13.1 10.7 (1.8)	n = 20 6.9-14.6 9.8 (2.3)	C	1 Compare controls	OFM	Good outcome with residual deformity
Turner et al. [134]	2006	Rheumatoid Arthritis	n = 12 27-64	n = 12 27-63	A	1 Compare controls	OFM	Differences found
Turner et al. [135]	2008	Rheumatoid Arthritis	n = 53 55.2 (11.7)	n = 74 56.4 (12.0)	A	1 Compare controls	OFM	Differences found
Van Hoeve et al. [136]	2015	Calcaneal fracture post surgery	n = 17 20-59 30.3 (14.8)	n = 13 25-81 50.6 (15.8)	A	1 Compare controls	OFM	Outcome related to PROM and quality of surgery
Wang et al. [137]	2010	Surgically treated ankle fracture	n = 18 19-64	n = 18 17-64	A	1 Compare controls	OFM	Quantify outcome
Woodburn et al. [138]	2004	Rheumatoid Arthritis	n = 5 *unreported*	n = 11 39-77	A	1 Compare controls	OFM	Differences found
Zhang et al. [139]	2017	Over-pronated feet (runners)	n = 17 21-41 25.9 (6.4)	n = 9 20-25 22.6 (1.9)	A	1 Compare controls	OFM	Differences found
Cobb et al. [20]	2009	Low mobile feet	n = 11 25.2 (3.2)	n = 11 24.5 (6.1)	A	1 Compare controls	own	Differences found
Van Gheluwe et al. [140]	2006	Hallux Limitus	n = 19 *unreported*	n = 19 20-55 24 (10)	A	1 Compare controls	own	Differences found
Wu et al. [81]	2000	Ankle arthrodesis	n = 10 20-35	n = 10 13-64	A	1 Compare controls	own	Differences found
Rao et al. [100]	2007	Diabetes	n = 15 56 (12)	n = 15 58 (11)	A	1 Compare controls	Rao	Differences found
Rao et al. [141]	2009	Midfoot arthritis	n = 20 48-78 58 (8)	n = 30 47-78 62 (7)	A	1 Compare controls	Rao	Differences found
Tome et al. [98]	2006	PTTD	n = 10 52.2 (7.3)	n = 14 56.8 (11.7)	A	1 Compare controls	Rao	Differences found
Hetsroni et al. [142]	2011	Calcaneal fracture post surgery	n = 20 37-60 52.1 (8.2)	n = 20 18-67 47.6 (9.9)	A	1 Compare controls	Rattanaprasert	Good outcome with residual deformity

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Table 2 (*continued*)

Reference	Year	Populations	Controls	Patients	age group	Application	Model	Summary of Outcome
Arnold et al. [143]	2014	Medial knee arthritis	n = 15 68.2 (9.7)	n = 15 67 (8.9)	A	1 Compare controls	RFM	Differences found
Caravaggi et al. [144]	2018	Flat foot	n = 10 13 (1)	n = 20 13 (1)	C	1 Compare controls	RFM	Postural and kinematic alterations
Chang et al. [145]	2014	Plantar fasciitis	n = 22 44 (10)	n = 22 42.9 (7.6)	A	1 Compare controls	RFM	Differences found (despite similar foot anthropometrics)
Van de Velde et al. [146]	2017	PTTD	n = 15 52 (10.1)	n = 15 P1:51 (12.2) P2:62 (13.7)	A	1 Compare controls	RFM	Differences found
Buldt et al. [147]	2015	Planus and Cavus feet	n = 37 25.1 (4.9)	n = 60 P1:24.2 (5.6) P2:27.2 (7.8)	A	1 Compare controls	Salford	Foot posture influences foot motion
Rattanaprasert et al. [79]	1999	Absent tibialis posterior	n = 10 22-45 30 (9)	n = 1 35	A	1 Compare controls / accuracy & reliability	Rattanaprasert	Differences found
Dingenen et al. [64]	2017	Chronic ankle instability	n = 12 23.6 (4.1)	n = 15 22.0 (2.7)	A	1 Compare controls / effect of taping	RFM	Differences to controls, but not with taping
Brodsky et al. [148]	2009	PTTD (post surgery)	n = 20 43-78	n = 20 37-75	A	1 Compare controls and contralateral limb	Milwaukee	Post op not different to controls
Powell et al. [25]	2013	High and low arched athletes	–	n = 20 18-28	A	1 Compare groups and compare models	OFM & RFM	OFM and RFM better at different things (10 high, 10 low)
Brodsky et al. [149]	2013	Total Ankle Arthroplasty	–	n = 46 43-85.3	A	1 Compare to contralateral limb	Milwaukee	Residual differences following surgery
Nawoczenski et al. [5]	2008	Hallux Rigidus	–	n = 20 34-63	A	2 Pre-post surgery (mid and long term follow up)	Rao	Better post surgery but still not normal
Canseco et al. [43]	2009	Hallux Rigidus	–	n = 19 34-75	A	2 Compare neutral and Pre-Post	Milwaukee	Differences found
Canseco et al. [44]	2012	Hallux Valgus	–	n = 19 24-72	A	2 Compare Pre-Post	Milwaukee	Improvement but still differences compared to normal
Giacomozzi et al. [45]	2006	Talocalcaneal coalition	n = 5 24-33	n = 8 8-24	A	2 Surgical compared to non-surgical	RFM	Differences found
Marks et al. [46]	2009	PTTD	n = 25 41.3 (12.5)	n = 20 P1:49.1 (7.5) P2:59.0 (8.9)	A	3 Comparison of surgical techniques / controls	Milwaukee	Differences found
Callaghan et al. [47]	2011	Post First MT Arthrodesis (2 types)	–	9 P1:58.2 (15) P2:60.5 (7)	A	3 Comparison of techniques	OFM	Differences between techniques (5 vs 4 subjects)
Caravaggi et al. [48]	2018	Flat foot	n = 10 11.2 (2.4)	n = 13 11.3 (1.6)	C	3 Comparison of techniques	RFM	Restoration of physiological alignment and frontal-plane mobility
Kothari et al. [49]	2016	Flat foot	n = 47 *8-15* *11.0 (2.9)*	n = 48 *8-15* *11.0 (2.9)*	C	4 Association with proximal joints	OFM	Increased prevalence of pain, but no associations found
Stebbins et al. [50]	2010	Cerebral Palsy	n = 15 6-14	n = 12 6-14	A	4 Outcome from surgery / relationship with other joints	OFM	Differences and correlations found / PRE-POST
De Ridder et al. [51]	2013	Ankle instability	n = 24 25.8 (1.9)	n = 53 P1:21.9 (3.3) P2:20.3 (1.9)	A	5 Compare copers and controls	Ghent	Differences found
Hosl et al. [52]	2014	Flat foot	n = 11 *age-matched*	n = 35 P1:11.0 (2.6) P2:11.6 (2.0)	C	5 Compare to controls, and between symptomatic/ asymptomatic	OFM	Differences found (14 symptomatic)
Deschamps et al. [53]	2013	Diabetes (with/ without neuropathy)	n = 13 57.7 (5.1)	n = 26 P1:62.8 (5.6) P2:63 (7.4)	A	5 Compare presence of neuropathy	RFM	Differences found (13 with / 13 without neuropathy)
Barton et al. [54]	2011	Patellofemoral pain syndrome	n = 20 23.4 (2.3)	n = 26 25.1 (4.6)	A	6 Association with Foot Posture Index	OFM	Correlations found
Kothari et al. [55]	2015	Flat foot	n = 47 12.0 (2.3)	n = 48 11.8 (2.0)	C	6 Association with Quality of Life	OFM	Correlation with frontal plane OFM
Thomas [56]	2006	Following ankle arthrodesis	n = 27 26-75 52.3 (15.8)	n = 26 18-83 53.5 (13.3)	A	6 Compare to PROM	own	Correlations found
Rao et al. [57]	2010	Diabetes	n = 15 56-12	n = 15 58-11	A	6 Association with pressure	Rao	Association with plantar loading
Krzak et al. [58]	2015	Hemiplegia - equinovarus	n = 20 11.8 (2.7)	n = 24 12.0 (4.1)	C	7 Classify foot types	Milwaukee	Classification not possible with single segment foot
Maurer et al. [59]	2014	Mid-foot break	n = 30 7-15 10.1 (2.5)	n = 30 5-16 9.6 (3.3)	A	7 Classification	mSHCG	Able to classify levels of severity

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Table 2 (*continued*)

Reference	Year	Populations	Controls	Patients	age group	Application	Model	Summary of Outcome
Turner et al. [60]	2008	Rheumatoid Arthritis	n = 53 55.2 (11.7)	n = 28 P1:57.8 (9.3) P2:53.8 (13.2) P3:64.7 (6.9)	A	7 Classification	OFM	Able to distinguish between different types of foot deformity
McCahill et al. [62]	2018	Clubfoot / CP	n = 15 6-14	n = 30 P1: 6-15 P2: 4-14	C	8 Repeatability	OFM	Comparable to control feet
Hyslop et al. [107]	2010	Psoriatic Arthritis	n = 9 29-59	n = 9 28-64	A	8 Repeatability	own	Repeatable
Sawacha et al. [29]	2009	Diabetes	n = 10 61.8 (4.3)	n = 10 64 (6.8)	A	8 Repeatability	own	Repeatable
Deschamps et al. [61]	2012	Foot deformity (adult)	–	n = 8 48 (15.4)	A	8 Repeatability	RFM	Repeatability comparable to neutral feet
Saraswat et al. [26]	2013	Pediatric planovalgus feet	n = 10 10.6 (1.6)	n = 11 10.7 (1.7)	C	8 Repeatability and sensitivity	mSHCG	Repeatability comparable to neutral feet

analyzed and categorized into primarily methodological ones or clinical applications of a previously reported technique. This resulted in the two parts of the present review paper.

The section on clinical application included papers that used an MFM to measure kinematic data during barefoot, level walking in a pathological population. Studies that only included typically developing subjects, or those focused on activities other than walking, were excluded.

3. Results and discussion

39 papers presenting an original MFM and 65 clinical papers met the inclusion criteria; these are discussed respectively in Parts I and II.

3.1. Part I: design of clinically relevant multi-segment foot models

3.1.1. Overview of current approaches to MFM

Table 1 includes all 39 MFMs; the nine with at least one corresponding clinical paper (Table 2) are in bold. These models differ in many factors: definition of foot segments, bony landmarks, type of marker clusters, anatomical frames, joint rotation convention - including 2D versus 3D measurements, neutral reference posture, offsets, etc. However, the major difference is in the number and selection of foot segments. While the tibia, rearfoot and forefoot are tracked by most techniques, the hallux – or the first metatarso-phalangeal joint – is rarely tracked, and the midfoot is tracked only by few models [15–17]. Medial and lateral forefoot subdivisions have also been proposed [15,18–21]. Even a twenty-six [22,23] segment foot model has been proposed, but its exploitation is limited to advanced musculo-skeletal modeling.

3.1.2. Comparison between MFMs

A number of studies have directly compared the performance of the most popular MFMs. Mahaffey et al. [24] used intra-class correlation coefficients to analyze the OFM, the Rizzoli Foot Model (RFM) and the Kinfoot [15] in 17 children on two testing sessions. A standard error for the measurements greater than five degrees was found respectively in 26%, 15%, and 44% of the kinematic parameters. In another paper by Powell et al. [25], the OFM and RFM were assessed in the context of foot function and alignment as possible predisposition factors for overuse and traumatic injury in athletes. Both models helped detect significant differences in frontal plane motion between high- and low-arched footed athletes, but the RFM was found to also track midfoot motion. While it was not the main scope of the study, a comparison between the modified Shriners Hospital for Children Greenville (mSHCG) foot model [26] and the OFM can be found in Maurer et al. [27]. Di Marco et al. [28] performed the most comprehensive comparative analysis by looking at the OFM, RFM, the Sawacha et al. [29] and Saraswat et al. [26] (i.e. the mSHCG) models. The best coefficient of multiple correlation between-sessions of the kinematic parameters during ground and treadmill walking was observed for the RFM (range 0.83 - 0.95). A recent paper [30] compared the experimental results obtained from five MFMs and found moderate to low variability as assessed with standard deviations. However, a single overall marker set was used, thus amalgamating the five different model sets. Because considerable offsets between joint motion patterns were observed, use of the same model and normative data were recommended when comparing findings between labs.

3.1.3. Validation of MFMs

MFM validation via direct assessment of bone motion is challenging, thus it is usually assessed in terms of repeatability of the relevant measurements (see last column in Table 1). Videofluoroscopy has shown that soft tissue artifact [31–33] can be as large as 16 mm during extreme foot rotations. The most direct measure of skeletal motion has been performed through in-vitro and in-vivo bone pins measurements. In-vitro, robotic gait simulators are used to replicate the biomechanical conditions of the stance phase of walking on foot cadaver specimens [34,35], while foot bones are tracked via intracortical pins instrumented with markers. However, because the procedure is highly invasive, fidelity in the replication of in-vivo conditions has been questioned. A number of validation studies have focused on the accuracy of the estimated in-vivo joint rotations in walking and running [36–42]. This required instrumented bone pins fixated to foot bones in volunteers under a small dose of local anesthesia. Motion of major foot joints was revealed to be very complex, and that of small joints, such as the talo-navicular, to be larger than expected - about ten degrees in the three anatomical planes. These studies also showed the kinematic differences between multi-bone segments, as measured by external skin clusters, and single bone pins. These experiments are limited by the small number of subjects, and not easily replicable for technical and ethical reasons.

3.2. Part II: evidence for the clinical use of MFMs

In total, 1457 pathological subjects were measured (mean 22 patients per study) along with 1155 controls (mean 18 subjects per study) across all studies. Of these papers, 14 included children (7 OFM, 3 mSHCG, 2 RFM, and 1 for HFMM and Milwaukee), with 311 patients and 228 control children. The populations measured represented a range of pathologies including different foot alignments (forefoot varus, flat feet, cavus feet, low mobile feet), soft tissue abnormalities, arthritis (n = 10), neurological conditions, diabetes (n = 4), bony fracture (n = 3), and assessment of surgical outcomes (n = 5). The patients' age

ranged from 5 to 85 years, whereas the control populations' from 6 to 78 years (Table 2).

Among the 65 clinical papers of the survey (Table 2), the OFM, Milwaukee and RFM models have been the most widely applied to pathological populations, respectively in 22, 13, and 10 clinical studies, all together representing about 2/3 of all these papers.

The application of the MFM for each of the studies was grouped into several categories, which are outlined below.

1. Cross-sectional comparison to a control population (n = 41)

Most of the papers included in the survey fell into this category. All studies reported at least one statistically significant difference in an MFM variable in the pathological population compared to the control population. A range of populations were reported across the studies including foot problems, ankle problems and even knee problems. This suggests that the MFMs are generally sensitive enough to distinguish pathological from control populations. The clinical relevance of some of these findings could however be questioned, due to the varied outcomes and the small differences - albeit statistically significant - detected between groups.

2. Assess the outcome of surgery (n = 4)

Four papers compared outcomes pre- to post surgery [5,43–45]. One of those [45] compared outcomes to a group that did not have surgery. The populations assessed included hallux rigidus, hallux valgus, cerebral palsy and talocalcaneal coalition. The models used included the Milwaukee, Rao, OFM and RFM models. All studies reported a significant difference in MFM variables when comparing pre- to post-surgery data. Interestingly, all studies also reported some residual deformity following surgery (either compared to a non-surgical group, or else compared to the laboratory reference data).

3. Compare between surgical techniques (n = 3)

Two papers assessed the difference in outcome when comparing different surgical techniques [46,47]. The first paper compared first metatarsal/phalangeal arthroplasty with arthrodesis to correct hallux valgus, while the second paper compared techniques for treating posterior tibial tendon dysfunction. In both cases, the authors were able to identify which technique was most effective at restoring normal foot motion. A third paper [48] compared the results of two types of poly-L-lactide bioabsorbable implants in bilateral subtalar arthroereisis. The models used were the Milwaukee, OFM, and RFM respectively.

4. Correlation with proximal joints (n = 2)

Another application of MFMs in the literature is to determine the correlation of foot pathology with more proximal joints [49,50]. Both papers that have applied an MFM in this way used the OFM model. The two pathologies represented were flat feet and cerebral palsy. In the study of flat feet, it was found that there was an increased incidence of pain in the hips and knees in the flat foot population. In the cerebral palsy group, it was found that a specific pattern of compensation could be identified in the proximal joints when an equinovarus foot posture was present. This suggests that MFMs have potential to assess the effect of foot deformity on the knees and hips, and to help with guiding where to target treatment.

5. Association with other symptoms (n = 3)

Three papers were identified that used an MFM to determine the correlation of foot deformity with other symptoms [51–53]. The Ghent, RFM and OFM models have all by been used in this way and have been applied in chronic ankle instability, diabetes, and flat foot. In the former group, it was used to identify which foot kinematics were associated with "copers" compared to "non-copers". The diabetic study was able to identify an association between MFM kinematics and the presence of neuropathy. While the flat foot study identified the correlation between MFM kinematics and the presence of foot pain.

6. Association with patient reported outcomes (n = 4)

MFM kinematics have also been correlated with patient reported outcome measures (PROMs) [54–57]. The models applied included the OFM and Rao models, and the pathological groups included those with flat foot, ankle arthrodesis and following surgery for calcaneal fracture. Each study found some kinematic characteristics that were significantly associated with quality of life, although these varied significantly across and within studies. It was also found that effectiveness of surgical intervention (as determined by the MFM) was correlated with the PROM score.

7. Classify foot types (n = 3)

Three papers used MFMs to classify severity of foot deformity [58–60]. The mSHCG model was used to classify type of midfoot break in cerebral palsy, the Milwaukee model was used to classify equinovarus deformity (also in cerebral palsy) and the OFM was used to characterize severity in rheumatoid arthritis. All studies were able to classify their populations into distinct groups. Interestingly, the study on equinovarus feet also attempted to classify foot type using a traditional, single segment model, and they were unsuccessful using this method. This implies that the greater detail measured using the MFM compared to a traditional model leads to greater precision in measuring foot deformity.

8. Repeatability in pathological populations (n = 5)

Finally, the repeatability of MFMs, as well as being measured in typically developing populations, has also been assessed in pathological groups. The models that have been applied include the RFM [61], OFM [62], mSHCG [26]. Populations include adult foot deformity, psoriatic arthritis, clubfoot, cerebral palsy (hemiplegia), absent tibialis posterior, pediatric planovalgus feet and diabetes. In each study, there was found to be acceptable repeatability of the models. In particular, the repeatability of the models was found to be similar to that found when applied to typically developing populations.

In summary, MFMs have now been successfully applied to numerous pathological populations. In most cases, this has involved a cross-sectional comparison with a typically developing, control population. Since over 40 studies including a range of ages and pathologies have now applied this technique in this way, it is reasonable to state that MFMs generally have adequate sensitivity to distinguish pathological feet from typically developing feet. The relevance of further studies that merely compare populations at one point in time might also be questioned. Future work could instead focus on determining the type and scale of deviations that result in clinically relevant findings.

In addition, there is some evidence currently in the literature that MFMs are also useful for the following applications: to determine the outcome of surgery, to differentiate between surgical techniques, to help determine primary problems in the lower limbs and therefore target treatment, to help explain symptoms such as pain, to demonstrate the importance of appropriate foot function for quality of life, and to classify the severity and type of foot deformity. However, for each of these applications, there is only limited (2–5 papers) evidence in the literature. Further work improving the body of evidence for each of these areas is warranted.

MFMs also have the potential to be applied to other research questions, such as predicting responders to treatment as well as the long-term effects of pathology. Longitudinal study designs would help progress the field of MFM research, particularly in pathological populations.

4. Concluding remarks

A large variety of MFMs based on different marker sets is currently available in the literature (Table 1). Some of these are available to users via simple-to-use software programs, which save time and resources in writing ad-hoc programs. Also according to a recent review [11], the most widely used MFMs are those supported by papers providing exhaustive instructions on marker positioning, data smoothing, definition of the anatomical frames, and joint conventions. This has also enhanced comprehension of the results, and usability and utility of the MFM [11].

New users should choose the most appropriate MFM according to the experimental conditions but should mainly consider the clinical or biomechanical hypothesis. Several factors should be taken into account

in selecting the most appropriate MFM for routine clinical applications, such as the capability of the set-up to track the markers, and its applicability to both the clinical population and the motor activities under investigation. The changes in kinematics following treatment should be much larger than the reliability of the corresponding measure. In addition, a compromise must be found between the necessary measurements which determine the number of segments, the 2D versus 3D calculations, and the number, quality and location of the available cameras.

Because of the large variety of MFMs currently available, a careful review of the existing techniques should be performed before developing a new one, though this may be necessary to address the specific needs of the research question. Using an existing, validated technique allows easier interpretation of the results via comparison with previously reported datasets. Since kinematic analysis of foot joints is highly sensitive to errors in marker placement, the involvement of experienced operators has also been recommended [63,64], together with programs of continuous training and quality assurance.

While foot kinematics can now be described with multiple degrees of freedom, several issues still remain. Due to the uncertainty in marker locations and anatomical frame definitions in some cases, normative databases associated with these MFMs are critical, and therefore should be available in every gait analysis laboratory [10]. To ensure an increased and coherent use of these techniques, standardization should be sought, in terms of anatomical landmark and frame definitions. In addition, another step forward would involve establishing a common terminology, which would avoid confusion in the interpretation of and comparison with the literature. The utilization of these MFMs is still uncertain in the presence of shoes or foot orthotics. In future clinical exploitations, the combination of MFMs with EMG and baropodometry could be of additional value [65,66]. Finally, novel technology in medical imaging, such as weight bearing CT [67], has great potential for combining measurement of skeletal deformities, as load is applied, with foot joint motion.

This review has highlighted the significant progress that has been made in the field of multi-segment foot modelling over the past few decades. Numerous models have now been described in the literature. A clear understanding of the model parameters and appropriate matching to the clinical question and laboratory set up are needed to select the most appropriate model for each application. There is a large body of evidence which suggests MFMs can be used to distinguish pathological from control populations. Further work is needed to extend the evidence for other applications, which would give increased confidence for using MFMs in clinical practice.

Conflict of interest

No conflict of interest has to be reported by the authors.

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