Abstract

Multiple marker sets and models are currently available for assessing foot and ankle kinematics in gait. Despite the presence of such a wide variety of models, the reporting of methodological designs remains inconsistent and lacks clearly defined standards. This review highlights the variability found when reporting biomechanical model parameters, methodological design, and model reliability. Further, the review clearly demonstrates the need for a consensus of what methodological considerations to report in manuscripts, which focus on the topic of foot and ankle biomechanics. We propose five minimum reporting standards, that we believe will ensure the transparency of methods and begin to allow the community to move towards standard modelling practice. The strict adherence to these standards should ultimately improve the interpretation and clinical useability of foot and ankle marker sets and their corresponding models.

Keywords

Kinematics; Foot and Ankle Biomechanics; Modelling
1. Introduction

Over the past decade the understanding of foot and ankle motion during gait has increased significantly due to pioneering bone pin analysis and the expansion of multi-segment foot models used to assess and quantify kinematic parameters in gait (Leardini et al., 2007, Lundgren et al., 2008, MacWilliams et al., 2003, Wolf et al., 2008, Carson et al., 2001, Nester et al., 2007). More sophisticated analytical methods often allow a better understanding of foot and ankle function. Where previously the foot has been considered as a single rigid segment in the literature, invasive in vivo measurements of foot kinematics have highlighted the complexity of the foot and the importance of those joints distal to the hindfoot (Lundgren et al., 2008, Wolf et al., 2008).

A wide range of foot & ankle modelling techniques are available, ranging from single-segment to complex multi-segment kinematic analyses. Single-segment foot models are typically used for the analysis of ankle joint kinematics (Collins et al., 2009, Scott and Winter, 1991, Moseley et al., 1996, Kitaoka et al., 2006). However, rigid single-segment foot models only define one foot segment relative to the shank (normally the ankle joint) and therefore cannot demonstrate the complex interaction of intricate joint articulations distal to the ankle joint. Given this knowledge, multi-segment marker sets and their corresponding models of the foot and ankle are now commonly used by gait labs around the world to describe the complex interaction of multiple joints of the foot and ankle (Kidder et al., 1996, Wu et al., 2000, Hunt et al., 2001, Carson et al., 2001, MacWilliams et al., 2003, Myers et al., 2004, Tome et al., 2006, Simon et al., 2006, Pohl et al., 2007, Leardini et al., 2007, Jenkyn and Nicol, 2007, Houck et al., 2008a, Sawacha et al., 2009, Cobb et al., 2009). The body of evidence to debate the use of multi-segment foot models has been subject to previous reviews (Rankine et al., 2008, Deschamps et al., 2011), yet the findings of a recent systematic identify that there is no adequate evidence to support the clinical use of multi-segment foot models
(Deschamps et al., 2011). This is a result of both a lack of reliability and validity studies, as well as
a lack of clearly defined and accepted standards for modelling the foot and ankle.

Despite the review by Deschamps et al., (2011) providing much needed clarity in regards to the
appropriate use of multi-segment foot models, their findings have been limited by the exclusion of
single segment foot models. This current review differs to those previous published as it critically
evaluates the concept of marker set and model development of both single segment and multi-
segment foot models. This systematic review aims to identify methodological considerations that
are of paramount importance in the description of clear, concise and transparent methods to
reproduce marker sets and their corresponding models. The recommendations of clear and
transparent reporting standards in this review are designed to ultimately translate into improved
clinical useability and validation or provide clear logic for the establishment of novel foot models.

2. Methods

2.1 Search Strategy

An electronic search of six databases (MEDLINE, Embase, Cinhahl, ISI Web of Science, Scopus
and SportDISCUS) was performed on the 25th November 2010. The search strategy used was “foot
model* AND human* AND kinematic* AND gait*”. Truncations were used to enable the search to
retrieve all possible variations of a specific root word. A snowball method was applied secondary to
the primary electronic search to identify literature that may have not been identified during the
electronic database searching process. This method involved searching the reference lists of articles
identified in the systematic literature search for potential relevant articles.

2.2 Eligibility criteria

Titles and abstracts of articles identified during the database searching were assessed by two
reviewers (CB and DT). Only peer-reviewed, full text articles published in the English language
were included. Only original three-dimensional foot and ankle marker sets and models were included in the review. Articles that did not establish an original model or only made minor modifications to a previously established model were excluded. It is acknowledged that the exclusion of marker sets and models that are not novel may limit the scope of the review of foot modelling literature as follow-up articles of original models may provide a better assessment of validity than the original paper. However, the scope of this review is to review original models and identify standards for reporting so that established marker sets and models can be validated in gait labs externally to those where the model was developed.

The purpose of this paper is to provide a critical appraisal of marker sets and models and not necessarily a definitive description of foot and ankle function. Thus for consistency throughout the review, data were only reported for normal or control feet and not pathological feet, as the scope of this review is the technicalities of foot modelling rather than dynamic foot function. The analysis of running biomechanics was excluded as it has been previously shown the kinematics of walking and running are different with large internal variation within populations (Mann and Hagy, 1980).

2.3 Data Extraction

Data were extracted from the literature based on themes of research design including population statistics, biomechanical modelling theory and the results of the study. Population data extracted included height, body mass and Body Mass Index (BMI) to provide information on the population that individual models were developed on, such as paediatrics or adults. Biomechanical modelling considerations included motion capture equipment (hardware and software), protocol development and model definition. Primary data extraction focussed on statistical analysis and whether the results were both supported by the conclusion, as well as the literature. In particular emphasis was placed on biomechanical modelling theory and technique.
2.4 Quality Assessment

The quality of literature reviewed was based on the modification of an appraisal criteria previously established for use in systematic reviews (Peters et al., 2010), designed to enhance the standard of the manuscript by minimising reviewer bias. The modified criteria consisted of 16 appraisal questions (Table 1) specifically related to methodology. The criteria previously developed in the literature (Peters et al., 2010) were modified to provide a more relevant critical appraisal of biomechanical modelling theory and technique in reference to marker set design and reproducibility. Two raters scored each article (CB and DT). Articles scored two points if they met the criteria, one point if limited detail were provided and zero if no detail were provided or the criteria were not mentioned in the article.

Each article was given a final score out of a possible 32 points. The overall score reflects the total assessment of the article and provides an assessment of the quality of the methodology. Where there were discrepancies between the rater’s score, the discrepancies were discussed at a consensus meeting and a consensus reached between the rater’s on the final score for each criterion. Where any major discrepancies could not be resolved or agreed upon by the rater’s, consultation would occur with an independent rater (GP) to resolve the discrepancy. However, this was not required. High methodological quality was defined as a score greater than 26/32 (Peters et al., 2010). These scores reflect the transparency and reproducibility of the methods, as well as the article’s interpretation of their stated results.

3. Results

3.1 Search Results

The systematic search process and results are presented in Figure 1. To ensure the search captured all relevant research, a secondary, first line snowball search was applied using the reference lists available in the articles identified in the database search. Although this may not have captured all
possible articles in the literature, this secondary systematic search identified a further four articles not included in electronic search. 17 original articles were included for the final review.

3.2 Population statistics

Population statistics extracted from the literature are presented in Table 2; these were deemed essential due to their role in model scaling. The articles included in the review typically had small sample sizes (range N=1-22). The average age reported ranged from 12.45 years to 64 years with mean Body Mass Index (BMI) ranging from 20.9 kg/m² to 33.7 kg/m². Six studies did not report or provide relevant data to calculate BMI. Only one article developed a model for a paediatric population (MacWilliams et al., 2003).

3.3 Segmental Parameters & Definition

All 17 articles reviewed defined the placement of markers via palpation of surface anatomical landmarks. Most articles used passive reflective markers mounted directly to the skin or mounted on a rigid plate and then mounted to the skin directly over anatomical landmarks. A combination of single markers and rigid clusters were used. Four reflective markers, mounted on a rigid plate equidistance apart to form a cluster were recommended to model the thigh and shank in Six Degrees of Freedom (6DOF) (Collins et al., 2009). These plates were mounted to the distal aspect of the segment to reduce soft tissue artefact.

The literature reports a wide range of models being developed that consider the foot as multiple segments (Table 3). 24% of the articles considered the foot as two segments (Scott and Winter, 1991, Kitaoka et al., 2006, Collins et al., 2009, Moseley et al., 1996), 12% as three segments (Wu et al., 2000, Hunt et al., 2001, Pohl et al., 2006), 35% as four segments (Carson et al., 2001, Myers et al., 2004, Stebbins et al., 2006, Kidder et al., 1996, Leardini et al., 2007, Houck et al., 2008b, Sawacha et al., 2009), 18% as five segments (Tome et al., 2006, Jenkyn et al., 2009, Cobb et al., 2009).
2009) and 6% as nine segments (MacWilliams et al., 2003). 6% of articles did not explicitly report the number of segments being analysed (Simon et al., 2006).

3.4 Quality Assessment

The results of the quality assessment are presented in Table 4, with 41% of articles assessed deemed high quality based on scoring at least 26/32. The majority of the articles reviewed provided methodologies deemed reproducible based on the reporting of segment parameters, marker positions, coordinate systems and the order of rotations. No article reviewed explicitly reported the study design used in their research. Only 29% articles explicitly stated the parameters of their model in regards to degrees of freedom or optimisation methods. Although the method of statistical analysis varied between articles, only 59% of articles reported the reliability of the marker set they were proposing.

3.5 Reliability Analysis

The quality assessment tool evaluated articles based on the reporting of reliability and variability of the data. A combination of intra-class correlation coefficient (ICC), coefficient of multiple correlations (CMC) and coefficient of variation (CV) were used in the literature. The hindfoot displayed good reliability and minimal variability. Houck et al (2008) reported intra-class correlation coefficient (ICC’s) of 0.96 for the hindfoot segment in the sagittal and coronal plane, demonstrating excellent reliability. Two articles presented means and standard deviations as measures of variability of the hindfoot (Carson et al., 2001, Simon et al., 2006). Between trial variability of the hindfoot ranged from 0.66 – 1.34° in the sagittal plane and 0.59-3.38° in the transverse plane. Only one paper reported hindfoot coronal plane results, demonstrating a variability of 0.57° (Carson et al., 2001).
The reliability and variability of the forefoot, which in the literature represents the metatarsals, was analysed by six articles (Hunt et al., 2001, MacWilliams et al., 2003, Houck et al., 2008b, Cobb et al., 2009, Simon et al., 2006, Carson et al., 2001). Three articles considered the forefoot as a rigid segment (i.e. including all 5 metatarsals) (Hunt et al., 2001, Carson et al., 2001, Simon et al., 2006). Hunt et al (2001) highlight the variability of the forefoot in the coronal plane, demonstrating CMC’s 0.4 and CV’s of 269%. Two articles report variability of a rigid forefoot as means and standard deviations (Carson et al., 2001, Simon et al., 2006). Between trial variability ranges between 0.57 – 1.45° in the coronal plane and 0.59-1.38° in the transverse plane (Carson et al., 2001, Simon et al., 2006). Between day variability of the forefoot in the sagittal plane was 0.69° (Carson et al., 2001). Between day variability ranges between 4.3-2.55° in the coronal plane and 6.4-7.29° in the transverse plane. One article reports between day variability of the forefoot in the sagittal plane of 3.2° (Carson et al., 2001). Three articles defined the forefoot as two segments (medial and lateral), or analysed the independent motion of the first metatarsal (Cobb et al., 2009, Houck et al., 2008b, MacWilliams et al., 2003). ICC’s were reported for the sagittal plane motion of the first metatarsal, demonstrating an excellent ICC of 0.94 (Houck et al., 2008b).

The reliability and variability of the hallux segment was analysed by four articles (MacWilliams et al., 2003, Houck et al., 2008b, Simon et al., 2006, Carson et al., 2001). An ICC of 0.95 was recorded in the sagittal plane (Houck et al., 2008b). Two articles report the standard deviation as a measure of variability (Carson et al., 2001, Simon et al., 2006). Between trial variability ranges from 1.95 – 1.97° in the sagittal plane and 0.57 – 3.2° in the coronal plane. Between day variability ranges from 2.8-3.0° in the sagittal plane and 2.87-3.3° in the coronal plane. One article presents variability in the transverse plane, reporting between trial variability of 0.96° and between day variability of 3.3° (Carson et al., 2001).
4. Discussion

The quality assessment undertaken in this review provides a resource for articles requiring assistance in both developing and appraising their research design and methodology, as it highlights aspects of methodology, data analysis and interpretation that should be evident in manuscripts written on the topic of foot and ankle biomechanics. Importantly, no reviewed articles scored less than 50% in the quality assessment, which indicates an acceptable standard of consistency in the reporting of key methodological considerations. Criteria assessed as being consistently well addressed in the literature included biomechanical modelling techniques, marker placement guidelines and the interpretation of results. However, a number of criteria were not addressed satisfactorily. A lack of detail to ensure reproducibility of methods was provided in regards to the description of the segment or local coordinate systems, the order of rotations used to describe joint kinematics, as well as the description of the parameters of the kinematic model in regards to its degrees of freedom and/or optimisation methods. These individual considerations have been identified by this review as important methodological considerations when designing kinematic marker sets and models given both their individual and combined effect on the magnitude and interpretation of the kinematic data collected. Subsequently reporting these details will aid other researchers analysing foot and ankle biomechanics, whether it be in the appropriate use of existing models or transparent establishment of new ones.

Although no formal standards exist for the palpation of anatomical landmarks, there was uniform support in the literature for the use of both skin-mounted and plate-mounted markers to define segment parameters. It is imperative that the marker set created can be used to define segment of research or clinical interest. One article in the literature proposed a new 6DOF marker set (Collins et al., 2009). The article suggests that 6DOF marker sets have improved construct validity than other commonly used marker sets (e.g. Helen Hayes or Conventional Gait Marker set) (Collins et al., 2009). However, like all marker sets and attachment methods, a 6DOF marker set is still
affected by soft tissue artefact (STA) and anatomical landmark identification previously described (Collins et al., 2009).

The apparent variability in the literature with regards to modelling methodology suggests that a logical and informed method or set of standards for determining the number of foot and ankle segments required in a model is yet to be determined (Nester et al., 2010). It is important for comparison within the literature that there are clear, concise and thorough accepted standards for the position of anatomical landmarks, the definition of segments, the order of segment rotations and the reporting of marker set reliability. There is uniform consensus in the literature that the hindfoot is composed of the calcaneus and talus, the midfoot composed of the navicular, cuboid and cuneiforms and the forefoot composed of the metatarsals. It is accepted that the hindfoot is modelled as an individual segment, yet its articulation with the shank is not indicative of talocrural function. If the purpose of the analysis is to describe ankle joint kinematics, it is recommended that the ankle is defined as the joint articulating between the shank segment and a single segment foot model used.

The findings of this review suggest that the midfoot and five metatarsals are often grouped as a combined segment. However, given the size of the midfoot and forefoot segments, it is difficult to simultaneously describe both the midfoot and metatarsus. This is further complicated when investigating shod kinematics. Consensus must be established for the true definition of the midfoot. Where possible, it is recommended that the midfoot be modelled independently of the forefoot given its known clinical function. The complexity of the midfoot articulations suggest that the segment could be in fact considered in more detail, however at this stage techniques do not appear to be well enough developed to model the midfoot in any way but as a single rigid segment. In cases where the midfoot and metatarsals cannot be accurately defined or there is not a need to isolate midfoot or metatarsal kinematics, it may be appropriate to group midfoot and forefoot segments as a
rigid body depending on the analytical question being asked. In either case, it is important to accurately describe the anatomical structures grouped together as a rigid segment and one must always stay true to the interpretation of what the kinematics of a particular segment actually mean. Further, if the biomechanical analysis requires an understanding of hallux and/or toe function, it is recommended that the hallux is modelled independently of toes 2-5, given its biomechanical function. These recommendations will provide a kinematic model that is useful in a clinical setting.

A number of limitations are evident in this systematic review. The search strategy focused on publications in the English language only, which may have excluded eligible manuscripts written in a different language. Further, the exclusion of abstracts and non-peer reviewed articles may have excluded some literature. We acknowledge our search strategy and first line snowball method may not have identified all possible literature surrounding kinematic marker sets and models. However, the search was done in a systematic way so that other researchers and clinical scientists could use the same search strategy and obtain the same results as in this review.

The quality assessment may be limited on the basis of the subjective interpretation of the independent reviewers in terms of quality assessment. Every effort has been made in this manuscript to provide transparent assessment guidelines of each criterion. Further, only two consensus meeting were required, where two criterions from two papers were disagreed upon. This equates to a disagreement over four criterion out of a possible 272. A disagreement level of 0.01% was considered satisfactory as an indication of the useability, objectiveness and repeatability of the quality assessment tool, especially between raters. Importantly, the consensus meeting resolved all discrepancies between raters and a final score for the criterion derived, without the involvement of a third rater (GP).
Reporting Standards

As a result of the review we would propose a set of five minimum standards for the reporting of the methodology design required to accurately and reliably develop and use foot and ankle marker sets and their corresponding models.

Standard One - The location and reliability of marker placement.

The rater applying markers must remain consistent within the study. The intra- and inter-rater reliability of applying calibration markers to define the proximal and distal boundaries of each segment must be reported. Reliable guidelines or established methods must be followed for the identification of marker position (i.e. palpation of underlying anatomical landmarks). Where such references are not available, the accuracy and reliability of marker placement must be reported. In the case of describing shod kinematics, the authors must clearly describe both the methods of identifying the position of markers through the shoe and as well as the methodology required to define the accuracy and repeatability of this process. The reference position used to define the anatomical frames must also be reported.

Standard Two – The definition of segment(s)

The kinematic model presented must clearly state the name of each of the segments as well as the underlying anatomy that the segment (rigid body) is assumed to represent. In the case of the foot and ankle, the model must highlight whether the model is a model of the foot (i.e. barefoot) or a model of the foot-shoe complex (i.e. shod). Regardless, the model must clearly define the interpretation/name of the joint created by two articulating segments. The methods to define the joint centre (i.e. functional or predictive) must be clearly defined for each joint in the model and referenced appropriately if required.
Standard Three – The definition of the segment coordinate systems

The orientation of the segment coordinate system must be clearly defined and/or referenced appropriately. The definition of the segment coordinate systems is directly influenced by the markers used to define the anatomical frame (Standard One).

Standard Four – The definition of joint parameters

The methods used to define the order of rotations of segments around joints must be clearly reported or referenced appropriately. The segment rotations and/or translations assumed to occur about each individual axis of a joint must be clearly defined and/or referenced appropriately. The degrees of freedom of each established joint in the model must be clearly defined. Methods to optimise the model must also be reported.

Standard Five – The reliability of joint kinematics

The effect that marker placement has on the underlying kinematics of a joint must be reported to ensure the identification of the differences expected in joint kinematics when two different raters apply the same marker set. This results in an assessment of clinical useability. The interpretation of kinematic differences within subjects must be made in the context of reporting the standard error of measurement for each marker set. Importantly, reliability and standard error of measurement statistics must be reported for each outcome measure about each axis.

Conclusion

Despite the number of kinematic foot and ankle models currently available, the critical factor in an optimal foot model is that the model must remain clear to its purpose, and what it does actually represent. It seems more than appropriate to define an optimal foot model at this stage as a model that can be created and/or adapted to represent specific segments of research or clinical interest. However, the complexity of the marker set and model used should always be indicative of the
complexity of the analytical question being asked as well as the number of individual segments needing to be analysed.

The quality assessment and critical appraisal process undergone in this review, clearly demonstrates the variability in the reporting of methodological design considerations. The review clearly demonstrates the need for a consensus of what methodological considerations to report in manuscripts/guidelines written on the topic of foot and ankle modelling. To address this problem, this systematic review provides a resource for foot and ankle researchers by providing clear definition standards to improve the design and reporting of foot and ankle marker set and modelling methodology.

**Conflict of interest statement**

None to declare


