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Finite element modelling of the foot for clinical application: A systematic review

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ABSTRACT

Over the last two decades finite element modelling has been widely used to give new insight on foot and footwear biomechanics. However its actual contribution for the improvement of the therapeutic outcome of different pathological conditions of the foot, such as the diabetic foot, remains relatively limited. This is mainly because finite element modelling has only been used within the research domain. Clinically applicable finite element modelling can open the way for novel diagnostic techniques and novel methods for treatment planning/optimisation which would significantly enhance clinical practice.

In this context this review aims to provide an overview of modelling techniques in the field of foot and footwear biomechanics and to investigate their applicability in a clinical setting.

Even though no integrated modelling system exists that could be directly used in the clinic and considerable progress is still required, current literature includes a comprehensive toolbox for future work towards clinically applicable finite element modelling. The key challenges include collecting the information that is needed for geometry design, the assignment of material properties and loading on a patient-specific basis and in a cost-effective and non-invasive way. The ultimate challenge for the implementation of any computational system into clinical practice is to ensure that it can produce reliable results for any person that belongs in the population for which it was developed. Consequently this highlights the need for thorough and extensive validation of each individual step of the modelling process as well as for the overall validation of the final integrated system.

1. Introduction

The ability to assess in vivo stresses that are developed inside the human foot during clinically relevant scenarios would significantly enhance our understanding on foot biomechanics and foot related pathologies. In the case of the diabetic foot, in particular, the ability to calculate internal stresses could shed new light on the phenomena that lead to ulceration and enable the optimisation of offloading strategies on a patient specific basis.

Despite this, there is no experimental method for the non-invasive assessment of internal soft tissue stress. Moreover, the complex geometry and nonlinear mechanical behaviour of the tissues of the foot render any analytical solution practically impossible without significant simplifications in terms of morphology and function [1].

Finite element (FE) is a powerful numerical method which can be utilised to solve problems with complicated geometry, material properties and loading. Therefore it is no surprise that current literature is rich in elaborate FE analyses on foot and footwear biomechanics. FE analyses have already given new insights in the phenomena associated with ulceration of the diabetic foot [2–9] and the offloading capabilities of diabetic footwear [4,6,10]. However, the actual contribution of FE analyses for the improvement of the therapeutic outcome of the diabetic foot is relatively limited [11]. This is mainly because FE modelling cannot be utilised outside the research domain to enhance and inform the everyday clinical management of the diabetic foot, or other foot related pathological conditions [11].

One of the main challenges for the implementation of FE modelling in everyday clinical practice is the development of reliable and affordable techniques for the subject specific modelling of the foot. Although the ability to use any modelling technique in the clinic is mainly determined by its ease of use, its non-invasive nature and low cost, the potential to actually enhance clinical practice is determined to a great extent by the accuracy and relevance of the information it can provide. Therefore, the main purpose of this review is to provide an overview of different modelling approaches and simulation techniques that have been used in the field of foot and footwear biomechanics and to investigate their applicability in a clinical setting and where possible also to comment on their accuracy.

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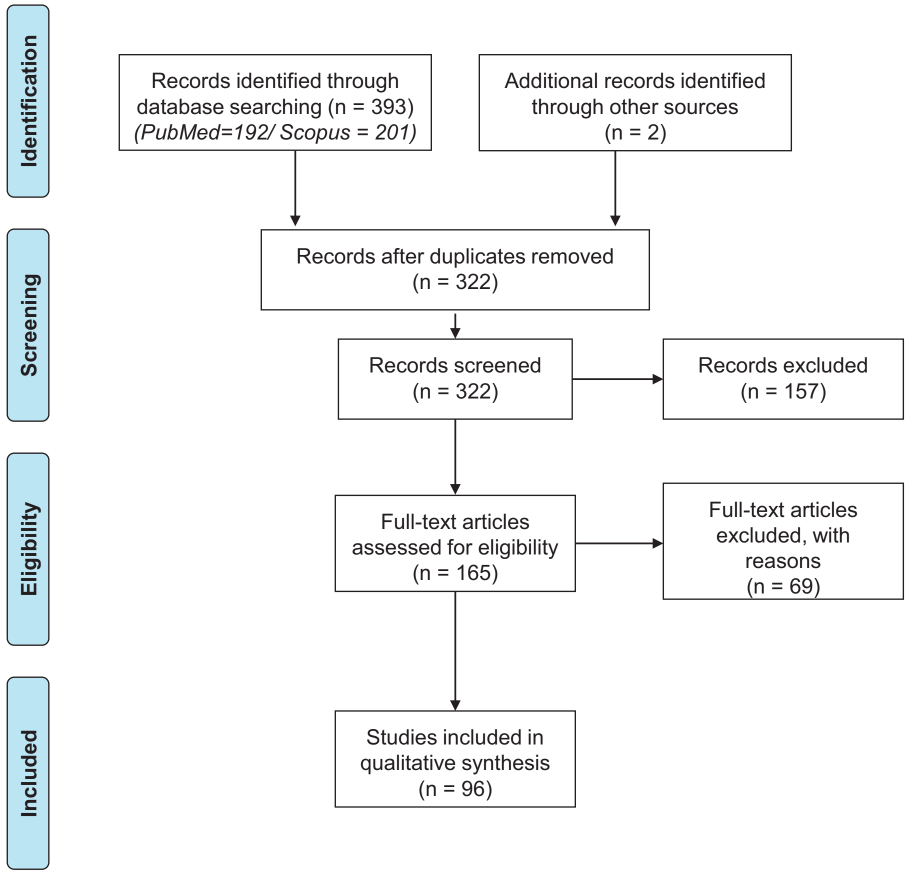

Fig. 1. Review flow chart (Prisma 2009).

2. Method

Relevant databases (Pubmed and Scopus) were searched using the keywords: (finite element [Title/Abstract]) AND (foot [Title/Abstract] OR shoe [Title/Abstract] OR plantar [Title/Abstract]) on 4th September 2015. The search was limited to studies with full texts published in English but there was no limitation in terms of publication date.

This review considered original papers on FE analysis of both the entire foot and parts of foot. In addition, FE analyses of footwear and insoles were also included. Analyses that were not focused on the entire foot or parts of the foot but on musculoskeletal structures proximal to the talus or the ankle joint were excluded. This means that studies on ankle, knee or hip prostheses/orthoses as well as studies on fracture and fracture fixation of the tibia and femur were all excluded. The papers which modelled foot with amputation were also excluded. After removing duplicates, the abstracts of 322 articles were screened and 165 articles that met the criteria for inclusion based on abstract were selected. Full text of all remaining articles were then assessed against the eligibility criteria leading to the selection of 96 articles which met the inclusion criteria (Fig. 1). Selected papers were analysed in terms of the methods used for: (a) geometry design, (b) the assignment of material properties, (c) the definition of boundary conditions and loading and (d) validation.

3. Results

The included papers covered a wide range of applications in the broader area of foot biomechanics and used a variety of different simulation strategies. More specifically 79% of reviewed papers simulated the healthy foot and the remaining 21% the pathologic foot. Thirty three percent (33%) in total were focused on the interaction between foot and footwear and 13% were related to the diabetic foot. Detailed information about every study that was included in this review can be found in Supplementary material (Table S1).

The methods that were used in these studies for designing the geometry, assigning the material properties, defining loading and for validation are presented below. In each case specific methods and their applicability in the clinical setting will be discussed after a brief overview of the range of methods used.

3.1. FE model design

Two main methodological approaches were found for geometric design: The use of realistic representations of foot geometry (89% of reviewed papers) or the use of idealised geometry (11% of reviewed papers).

According to the first methodological approach the geometry is directly defined based on medical imaging through a segmentation and reconstruction process. Early approaches to the FE modelling of the foot utilised X-ray images [12–15] but almost all reviewed studies published after the year 2000 were based either on Magnetic Resonance Imaging (MRI), or Computer Tomography (CT) images (Table S1). Sixty four percent (64%) of these studies presented detailed 3D models of the entire foot [3,12–69] while 10% used detailed 3D models focused on specific parts of the foot [4,5,70–77]. Fourteen percent (14%) of reviewed studies developed 2D models of a cross-section of the foot based on a single CT/MRI image [2,6,10,78–88]. Finally only one study (1% of reviewed