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Simple finite element models for use in the design of therapeutic footwear

Thomas A. Spirka [a], Ahmet Erdemir [b], Susan Ewers Spaulding [a], Ann Yamane [a], Scott Telfer [a,c], Peter R. Cavanagh [a,*]

[a] Department of Orthopaedics and Sports Medicine, University of Washington, Seattle, WA, USA
[b] Computational Biomodeling (CoBi) Core and Department of Biomedical Engineering, Lerner Research Institute, Cleveland Clinic, Cleveland, OH, USA
[c] Institute of Applied Health Research, Glasgow Caledonian University, Glasgow, UK

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ABSTRACT

Therapeutic footwear is frequently prescribed in cases of rheumatoid arthritis and diabetes to relieve or redistribute high plantar pressures in the region of the metatarsal heads. Few guidelines exist as to how these interventions should be designed and what effect such interventions actually have on the plantar pressure distribution. Finite element analysis has the potential to assist in the design process by refining a given intervention or identifying an optimal intervention without having to actually build and test each condition. However, complete and detailed foot models based on medical image segmentation have proven time consuming to build and computationally expensive to solve, hindering their utility in practice. Therefore, the goal of the current work was to determine if a simplified patient-specific model could be used to assist in the design of foot orthoses to reduce the plantar pressure in the metatarsal head region. The approach is illustrated by a case study of a diabetic patient experiencing high pressures and pain over the fifth metatarsal head. The simple foot model was initially calibrated by adjusting the individual loads on the metatarsals to approximate measured peak plantar pressure distributions in the barefoot condition to within 3%. This loading was used in various shod conditions to identify an effective orthosis. Model results for metatarsal pads were considerably higher than measured values but predictions for uniform surfaces were generally within 16% of measured values. The approach enabled virtual prototyping of the orthoses, identifying the most favorable approach to redistribute the patient's plantar pressures.

1. Introduction

Therapeutic footwear is often prescribed to redistribute plantar pressures and attenuate peak pressures in at-risk regions of the foot both to relieve pain in the case of patients with rheumatoid arthritis and to reduce the risk of plantar ulcers in patients with diabetes (Hennessy et al., 2012; Boulton et al., 2004). However, very few guidelines exist as to how these interventions should be designed and what effect such interventions actually have on the plantar pressure distribution (Waaijman et al., 2012). In addition, how footwear designs can be individualized to accommodate patient-specific foot anatomy is not clear. Frequently, the design of an intervention is based on the clinical experience of the pedorthist.

Finite element analysis has the potential to assist in the design process by allowing the clinician to evaluate the effectiveness of many different interventions in order to identify which solution could provide the greatest benefit to a given patient, without having to actually build and test each modification. Several authors have proposed the construction of detailed foot models that incorporate as many of the structures of the foot as possible (Franciosa et al., 2012; Qiu et al., 2011; Hsu et al., 2008; Cheung and Zhang, 2008; Actis et al., 2008) for the purpose of designing footwear. However, development of a full-foot patient-specific model can be a labor-intensive and time-consuming process which frequently results in a computationally expensive model. This limits the feasibility of utilizing models in a translational sense, for a large number of patients and for the often iterative process of footwear design. Simplified two-dimensional models of

* Corresponding author at: Department of Orthopaedics and Sports Medicine, University of Washington Medical Center, Room BB1065D/Box 356500, 1959 NE Pacific Street, Seattle, WA 98195, USA.
E-mail address: cavanagh@uw.edu (P.R. Cavanagh).

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the foot with somewhat limited loading conditions have been proposed by Yarnitzky et al. (2006). The goal of the current work was to determine if a simplified 3D model customized for gross patient-specific anatomy could be used to assist in the design of footwear interventions to reduce plantar pressures at targeted forefoot regions. The approach is illustrated by a case study of a diabetic patient experiencing high pressures and pain under the fifth metatarsal head and elevated pressure under the first metatarsal head.

2. Methods

2.1. Finite element representations of the metatarsal region of the foot

Computed tomograms (CTs) of the left foot were acquired with approval of the University of Washington Institutional Review Board from a 46 year-old male (height = 1.8 m, weight = 74 kg) with Type I diabetes. He presented with callus under the 1st and 5th metatarsal heads, pain under the 5th despite dense peripheral neuropathy, and a plantarflexed 1st ray. Images were acquired on a GE Lightspeed VCT (GE Medical Systems, Milwaukee, WI) with a slice thickness 0.625 mm. Image resolution was 512 pixel × 512 pixel with pixel size of 0.6 mm × 0.6 mm. The image processing software Scan IP (Simpleware Ltd., Exeter, UK) was used to acquire the measurements listed in Table 1. Briefly, the minimum tissue thickness beneath each metatarsal head (MTH), the length of each metatarsal bone, the maximum width of each MTH, the distance between the center point of each MTH relative to the neighboring MTH and the angle the metatarsal bone made with a straight line running tangent to the plantar surface were all measured. The accuracy and reliability of the above measurements is observer-dependent: for example, five repeat measurements of tissue thickness under MTH2 and the width of MTH2 made by two observers resulted in mean values that differed by less than 0.1 mm and 0.5 mm, respectively, but the coefficients of variation for the two observers were 1%/3% and 5%/11% (observers 1 and 2, thickness/width).

Measurements of gross metatarsal anatomy and tissue thickness were incorporated into a finite element model of the metatarsal region of the foot that utilized simple shapes to represent the bones and the surrounding tissue utilizing Abaqus CAE Version 6.10 (Simulia, Providence, RI). The metatarsal bones were modeled as rigid structures using a combination of a cylinder and a sphere (Fig. 1a). The diameter of the sphere representing the metatarsal head was based on the

Table 1
Measurements acquired from CT scan for construction of the simplified model.

	1st Metatarsal	2nd Metatarsal	3rd Metatarsal	4th Metatarsal	5th Metatarsal
Width of MTH (mm)	25	15	13	13	13
Medial(+)/lateral(−) distance relative to MTH3 (mm)	41	17	0	−15	−35
Anterior(+)/posterior(−) distance relative to MTH3 (mm)	0	0	0	−10	−23
Thickness of tissue under MTH (mm)	8*	14	10.5	8.5	6.5
Angle relative to plantar surface (°)	30	29	25	23	22
Length of MTH (mm)	64	73	74	77	74

* Average thickness underneath the lateral and medial sesamoids

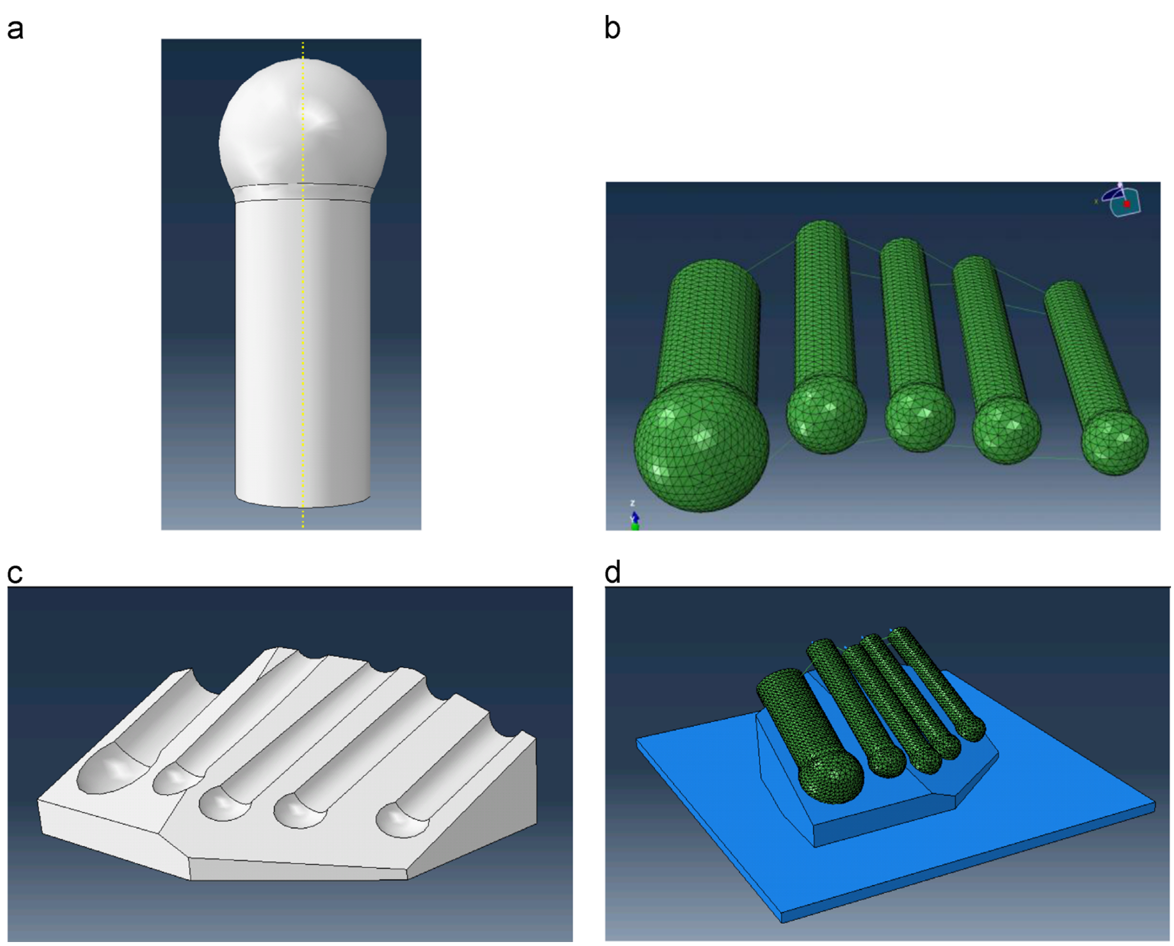

Fig. 1. Model design and construction: (a) simplified shapes used to define the metatarsal bones. (b) Bone orientation showing relative position and angle relative to the plantar surface. (c) Geometry of the soft tissue block. (d) Final model illustrating the barefoot condition.