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Evaluation of a Kinematically Driven Finite Element Footstrike Model

Iain Hannah,[1,2] Andy Harland,[1] Dan Price,[3] Heiko Schlarb,[3] and Tim Lucas[3]

[1]Sports Technology Institute, Loughborough University, Loughborough, UK;

[2]INSIGNEO Institute for *in silico* Medicine, University of Sheffield, Sheffield, UK;

[3]adidas AG, Herzogenaurach, Bavaria, Germany

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Correspondence Address: Iain Hannah. *Tel.: +44 (0) 7745 833 099, fax: +44 (0)1509 564 820.*

E-mail address: i.hannah@sheffield.ac.uk

Running Title: *A Kinematically Driven FE Footstrike Model*

Abstract (199 words)

A dynamic finite element model of a shod running footstrike was developed and driven with six degree of freedom foot segment kinematics determined from a motion capture running trial. Quadratic tetrahedral elements were used to mesh the footwear components with material models determined from appropriate mechanical tests. Model outputs were compared to experimental high speed video (HSV) footage, vertical ground reaction force (GRF) and centre of pressure (COP) excursion to determine whether such an approach is appropriate for the development of athletic footwear.

Although unquantified, good visual agreement to the HSV footage was observed but significant discrepancies were found between the model and experimental GRF and COP readings (9% and 61% of model readings outside of the mean experimental reading ± 2 standard deviations respectively). Model output was also found to be highly sensitive to input kinematics with a 120% increase in maximum GRF observed when translating the force platform 2 mm vertically.

Whilst representing an alternative approach to existing dynamic finite elements footstrike models, loading highly representative of an experimental trial was not found to be achievable when employing exclusively kinematic boundary conditions. This significantly limits the usefulness of employing such an approach in the footwear development process.

Keywords: finite element analysis, athletic footwear, running, kinematics, ground reaction force

Word Count: 1995

Introduction

In order to satisfy increasing consumer demand for enhanced performance, athletic footwear brands invest significantly in the design of novel footwear technologies. Mechanical, biomechanical and user wear trials are all typically employed in an iterative design process but this approach is both time consuming and expensive.[1] As a result, several leading brands have begun to adopt computer aided engineering (CAE) techniques in order to minimise costs and reduce development times.[2,3]

The potential utility of a rigid-body-dynamics based foot-footwear-floor contact model was reported by Wright et al.[4] and has the potential to allow the mechanical performance of prospective footwear designs to be evaluated in a virtual environment, avoiding the variation inherent in human testing[5] and reducing the need for physical prototyping. A number of finite element (FE) footstrike models have been reported but these studies have been limited to two dimensional analyses,[6,7] with quasi-static loading[8] and largely simplified boundary conditions applied.[9,10]

In order to provide an accurate prediction of an item of footwear's response to loading, a footstrike model would have to contain accurate footwear geometries, an appropriate mesh and, sophisticated material models characteristic of those used in modern athletic footwear. Most importantly, the boundary conditions used in any model must be representative of the complex, multiaxial and dynamic loading applied to the footwear during a footstrike.

This paper presents the first dynamic FE model of a shod footstrike to employ kinematic boundary conditions determined directly from the motion capture of experimental running trials. The sensitivity of the model to input kinematics is evaluated with its ability to apply biomechanically representative load conditions investigated through comparison of the modelled and experimental loading conditions. This paper thus aims to answer whether it would be appropriate to adopt such an approach in the development of athletic footwear.

Methods

Determining Boundary Conditions

Boundary conditions typical of a shod heel-toe running footstrike were determined from six biomechanical overground motion capture trials performed by a healthy, male subject (age: 24 years, height: 1.76 m, mass: 69 kg). The participant gave informed ethical consent to take part in the study, which was conducted in accordance with the protocol approved by the [Name deleted to maintain the integrity of the review process] Ethical Advisory Committee.

Ten spherical retroreflective markers were attached to the shod left foot of the subject in accordance with the Heidelberg Foot Measurement Method.[11] The subject wore a simple athletic shoe manufactured specifically for the test which consisted of an ethylene-vinyl acetate (EVA) midsole, a blown rubber outsole, and simple laced upper. Running speed was controlled to be $4.0 \pm 0.1\ m \cdot s^{-1}$ with reflective laser timing gates.

The 3-D trajectories of each marker were recorded with a network of 12 infrared cameras (Vicon, UK) sampling at 200 Hz. Vertical ground reaction force (GRF) was measured at a sample rate of 1000 Hz with a piezoelectric force platform (Kistler, Winterthur, Switzerland) with synchronised high speed video (HSV) footage obtained with dual cameras (Photron, Tokyo, Japan).

Similar to Carson et al.,[12] the biomechanical model employed consisted of three rigid segments: a rearfoot calcaneal segment, a metatarsal segment including the five metatarsal rays and a forefoot segment encompassing all fourteen phalangeal bones (Fig. 1). The foot model was built in Visual3D (C-Motion, Germantown, MD) from a static standing trial performed by the subject. The 3-D translations and rotations of each segment were determined by subsequently performing an inverse kinematics analysis of each dynamic trial.

In accordance with ISB guidelines,[13] rotation amplitudes for each functional foot segment were calculated about the laboratory origin with a Cardan sequence of X (M-L), Y (A-P), Z (dorsoventral). The six degree of freedom kinematic data of each segment were then filtered with a fourth order low-pass bidirectional Butterworth filter with a cut-off frequency of 8 Hz.

When fitting the static model to each dynamic trial, typical segment residual values[14] of 2 - 4 mm were obtained. The trial with the lowest aggregate segment residual value (calcaneus: 2.0 mm, metatarsals: 2.3 mm, phalanges: 2.2 mm) was selected for finite element modelling.

Finite Element Modelling

To allow for the positioning of the footwear midsole and outsole geometries in the laboratory coordinate system, the three dimensional geometry of the lasted shoe and its attached markers was captured with an ATOS I 800 Digitizer stereo fringe projection scanner (GOM mbH, Braunschweig, Germany). The pose of the scanned geometry was then determined by rigidly registering the ten scanned markers with the marker locations measured from the last frame of the biomechanical trial captured before contact with the force platform. The average registration residual was 4.0 mm. Surface-based CAD geometries of the midsole and outsole obtained from manufacturing tooling profiles were subsequently aligned to the scan geometry and exported for meshing.

The three functional segments of the foot were represented by rigid plates created on the top surface of the midsole and meshed with 2-D triangular shell elements (Fig. 1). The dimensions of each of these plates were determined by identifying the anteroposterior (A-P) and mediolateral (M-L) extremities of each bony segment from a sagittal MR scan (Siemens AG, Munich, Germany) of the foot-ankle complex. A gap of 10 mm was left at the metatarsophalangeal joint to allow relative motion to occur.

[Figure 1 near here]

The six degree of freedom foot segment kinematics computed from the experimental trial were represented in the model as transient translational and rotational displacement boundary conditions applied to each of the three foot plates. These loads were applied to a rigid body reference point created at each segment’s local origin in the biomechanical model.

Preliminary analyses indicated that further constraint was required at the midfoot and metatarsophalangeal intersegmental joints. This was achieved by introducing a homogenous 3-D structure with the geometry of a foot prosthesis (Otto Bock, Duderstadt, Germany) to the assembled model and coupling the nodes of its plantar surface to that of the calcaneal, metatarsal, and phalangeal plates. No loading was applied to the foot geometry as its role was solely to apply damping to the system and act as a visual aid when validating the model.

A mesh convergence study was performed in order to determine a mesh density that would allow for a manageable solve time whilst still outputting a converged solution. The convergence criteria selected was maximum vertical ground reaction force with the tolerance level chosen to be a change of less than 2%. All 3-D volumes were subsequently meshed with modified quadratic tetrahedral elements as they have been shown to perform consistently well in a range of foot and footwear simulations.[15] The laboratory force platform was modelled with rigid, shell elements.

Petre et al.[16] called into question the results of several studies which determined the material parameters of FE elastomeric foams models from single modes of testing. The stress-strain response of EVA was thus characterised for multiple modes of deformation: uniaxial tension, simple compression, and planar shear (5565 universal testing machine, Instron, Norwood, MA). Using Abaqus 6.12 (Dassault Systèmes, Vélizy-Villacoublay, France) it was found that the most appropriate representation of the EVA midsole's response under loading could be achieved with a first-order hyperfoam strain energy density function.[17]

Similarly, material parameters for the blown rubber used in the outsole were determined from uniaxial tension and simple compression tests. The material was found to be best represented with a third-order hyperelastic strain energy function.[17] Near incompressible material behaviour was ensured by defining a Poisson's ratio of 0.475.

Finally, an incompressible second-order hyperelastic material model was used to characterise the behaviour of the homogenous foot geometry with material parameters reverse engineered to provide sufficient constraint at the midfoot and metatarsophalangeal joints included in the model. Materials parameters are not reported as they have been developed in a commercially sensitive environment.

The model outputs of interest were found to be uninfluenced by the definition of tangential contact. As such, frictionless penalty contact was defined between the rigid force platform and all deformable bodies in the analysis. Adjacent foot and footwear surfaces were also constrained with kinematic ties. The analysis was submitted to the Abaqus/Explicit solver.

Validation of the modelling approach was attempted by comparing the model GRF and COP outputs to the experimental trials from which the applied boundary conditions were determined. An acceptable result was considered to fall within two standard deviations (sd) of the mean experimental value (n=6) and could thus be considered representative of the modelled movement task.[18]

The sensitivity of model output to the applied kinematics was investigated by performing two further analyses in which the position of the force platform instance was translated vertically ± 2 mm. A translation of 2 mm was selected to correspond with the minimum segment residual value observed.

Results

[Figure 2 near here]

Whilst unquantified, good visual agreement was seen between model field output and high speed video footage of the corresponding biomechanical trial (Fig. 2). This is however to be expected for a kinematically driven model.

[Figure 3 near here]

Model GRF output displayed distinct impact and propulsive force peaks but overall agreement to the experimental trial was poor with only 9% of model outputs falling within two standard deviations (sd) of the mean experimental value (Fig. 3). The simulated impact force peak was 26% lower and the impact force peak 14% higher than during experimental testing.

This indicates that the discrepancy between simulated and experimental loading profiles is not due to a systematic error. The overall root-mean-square (RMS) deviation was 143 N with the total duration of the stance phase also reduced by 0.034 s relative to the modelled experimental trial.

[Figure 4 near here]

Agreement to experimental COP excursion was also found to be poor with only 45% (A-P) and 78% (M-L) of model outputs registering within two sd of the experimental means. Relative to the experimental trial modelled, RMS deviations of 13.7 mm (A-P) and 8.7 mm (M-L) were observed with the maximum residual found to be 24.7 mm. The first 0.01 s of the footstrike was omitted from the analysis as experimental COP measurement can be unreliable when the vertical GRF is small.[19]

Finally, the modelling methodology was found to be highly sensitive to the applied kinematics with a 2 mm adjustment in the position of the force platform resulting in a maximum change in model GRF of 2.3 kN. A translation of +2 mm along the vertical axis was found to increase the impact force peak by 52% and the propulsive force peak by 120%. Similarly, translating the force platform -2 mm was found to reduce the impact and propulsive force peaks by 34% and 44% respectively.

Discussion

The utility of a kinematically driven footstrike model has been evaluated in this paper by determining if the reported model was capable of applying simulated loading representative of a shod footstrike. The approach of employing experimentally measured kinematic boundary conditions is novel and agreement to HSV footage was good but only 9% of model GRF outputs and 61% of COP excursion readings fell within two sd of the experimental means, thus failing the validation criteria. This indicates that the proposed methodology cannot apply loading representative of a running footstrike.

This can be explained by the demonstrated sensitivity of the model to the defined boundary conditions (Fig. 5) and the uncertainty inherent in their measurement. The registration technique employed to position the footwear relative to the force platform resulted in an average residual of 4 mm at each marker location. Segment residual values of 2 – 4 mm were calculated when fitting the static foot model to a dynamic trial and movement artefact of the in-shoe foot segments relative to the shoe-mounted markers[20] was entirely unaccounted for. By comparison, adjusting the position of the force platform by only 2 mm increased the applied loads by up to 120%.

It can thus be concluded that an FE footstrike model driven exclusively by foot segment kinematics, as described in this study, cannot accurately represent the complex, dynamic loading characteristics of a human footstrike. Without greater confidence in the 3-D kinematics of the foot segments, a highly accurate representation of experimental loading patterns will not be achievable. This greatly limits the value of such an approach when evaluating prospective footwear designs and it is therefore suggested that an alternative, force driven approach is pursued.

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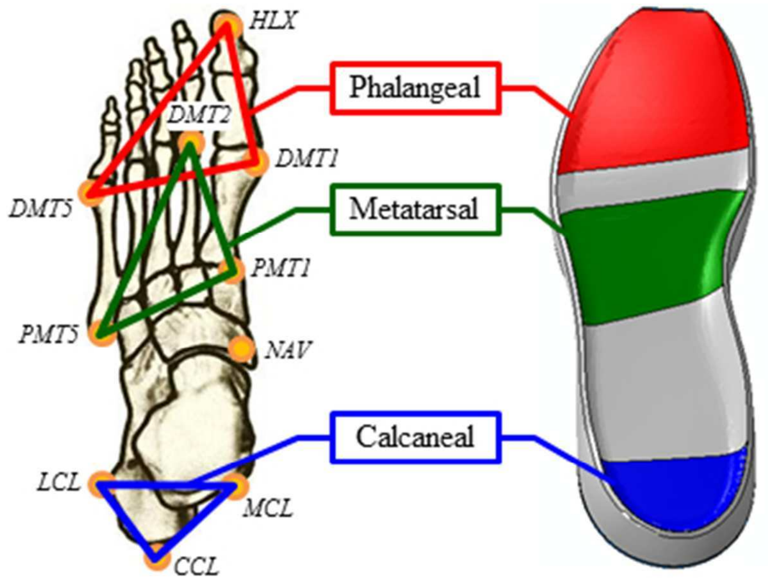
Figure Captions

Figure 1 - Three segment foot model encompassing calcaneal, metatarsal and phalangeal segments and footwear instances with corresponding rigid foot segment plates.

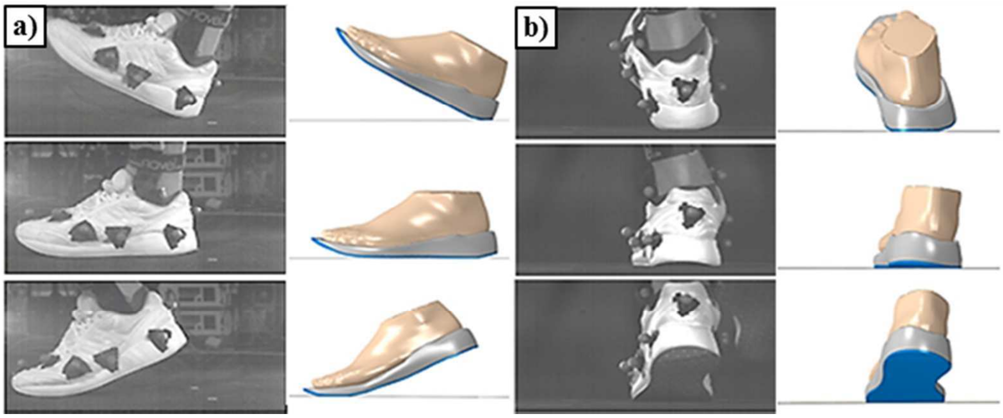
Figure 2 - Visual comparison of model field output to experimental HSV footage at heelstrike, midstance and push-off. (a) Lateral view. (b) Posterior view.

Figure 3 - Comparison of modelled and experimental vertical ground reaction forces with impact and propulsive force peaks shown.

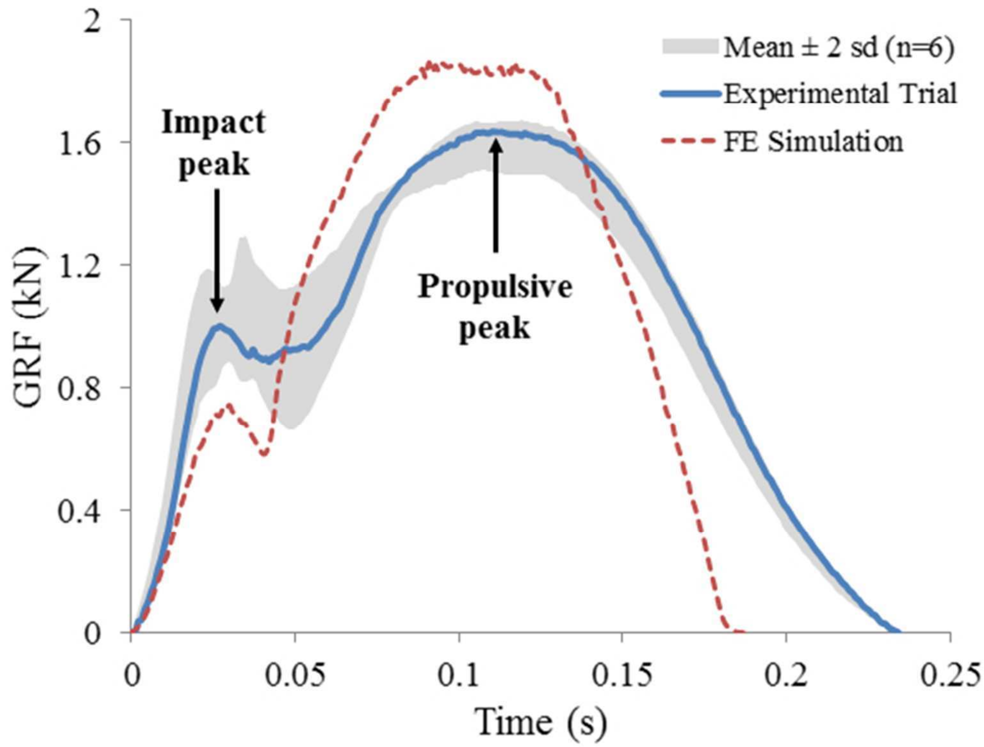
Figure 4 - Comparison of simulated and experimental COP excursion (a) Anterposterior axis. (b) Mediolateral axis.



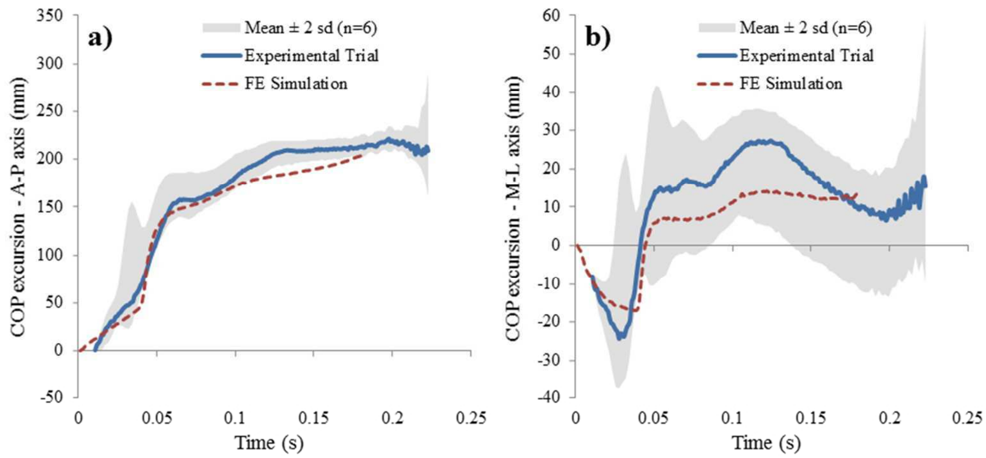
Three segment foot model encompassing calcaneal, metatarsal and phalangeal segments and footwear instances with corresponding rigid foot segment plates.
102x75mm (96 x 96 DPI)



Visual comparison of model field output to experimental HSV footage at heelstrike, midstance and push-off. (a) Lateral view. (b) Posterior view.
185x76mm (96 x 96 DPI)



Comparison of simulated and experimental vertical ground reaction forces with impact and propulsive force peaks shown.
159x119mm (96 x 96 DPI)



Comparison of simulated and experimental COP excursion (a) Anterposterior axis. (b) Mediolateral axis.
238x111mm (96 x 96 DPI)