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Centre of pressure output in a kinematically driven finite element footstrike model

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Abstract

A dynamic finite element model of a shod footstrike was developed and driven with six degree of freedom kinematic boundary conditions calculated from a motion capture running trial. Linear tetrahedral elements were used to mesh the midsole and outsole of the footwear with material models determined from appropriate mechanical tests. The model was validated by comparison to experimental high speed video footage and vertical ground reaction force.
92% of model centre of pressure (COP) output readings were found to fall within an experimental error tolerance of ± 20 mm. To investigate the sensitivity of COP output location to the footwear's initial orientation the position of the floor instance was altered by translating ± 2 mm vertically and rotating ± 1° about the sagittal and frontal axes. In comparison to the base model, COP output was found to be most sensitive to rotation about the sagittal axis with a maximum change in location of 69mm. Output location was altered by up to 26 mm and 19 mm for vertical translation and rotation about the frontal axis respectively. These values are significant and draw into question the validity of the loading conditions that can be applied with a kinematically driven footstrike model.

Keywords: Finite element analysis; footwear; running; kinematics; centre of pressure

1. 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

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consuming and expensive [2]. As a result, several leading brands have begun to adopt computer aided engineering (CAE) techniques in order to minimise costs and reduce development times [3, 4].

The development of a finite element footstrike model would allow the performance of prospective footwear designs to be evaluated in a virtual environment, avoiding the variation inherent to human testing [5] and reducing the need for physical prototyping. Centre of pressure (COP) is a key indicator of load distribution under the foot [6] and is therefore of significant interest in the footwear development process. In order to provide an accurate prediction of footwear performance, a finite element footstrike model must thus be capable of outputting accurate COP readings.

A number of finite element footstrike models have been reported but these studies have been limited to two dimensional analyses [7, 8], with loads applied quasi-statically [9] and largely simplified boundary conditions [10, 11]. This study presents a novel finite element footstrike modelling methodology with kinematic boundary conditions determined directly from motion capture running trials. The feasibility of using such boundary conditions to represent the complex, dynamic loading characteristics of a human footstrike and output accurate COP readings is also evaluated.

2. Methods

2.1. Generating Boundary Conditions

A healthy, male subject (age: 24 years, height: 1.76 m, weight; 69 kg) with a rearfoot striking running style was used as the subject for all biomechanical motion capture trials. Ten spherical retroreflective markers were attached to the shod left foot of the subject in accordance with the Heidelberg Foot Measurement Method [12]. The athletic shoe used consisted of a simple ethylene-vinyl acetate (EVA) midsole, a blown rubber outsole, laced upper and was fitted with a standard foam sockliner. Running speed was controlled with reflective laser timing gates with only trials completed at 4.0 ± 0.1 ms^{-1} accepted.

The linear kinematics of each marker were recorded with a network of 12 infrared MX cameras (Vicon, UK) sampling at 200 Hz. The use of a multi-output TTL trigger box enabled synchronised high speed video (HSV) footage to be obtained for each trial with dual cameras (Photron, Japan) orientated laterally and posteriorly to the force platform and capturing at 200 frames per second. The ground contact phase of gait (heelstrike – toe-off) was identified using a piezoelectric force platform (Kistler, Switzerland) networked to the host PC with a vertical ground reaction force (GRF) threshold of 15 N. Data frames outside of this period were discarded.

Similar to Carson et al. [13] and based on rigid-body assumptions, dynamic foot motion was characterised by defining three functional foot segments; a calcaneal segment, a metatarsal segment including all five metatarsal rays and a phalangeal segment which encompassed the fourteen phalangeal bones (Fig 1). No kinematic constraints were applied between segments allowing for six degree of freedom relative motion at the midfoot and metatarsophalangeal joints.

Raw kinematic data were filtered with a fourth order low-pass bidirectional Butterworth filter with a cut-off frequency of 8 Hz. The three segment model of the foot was constructed with Visual3D software (C-Motion, USA) with the zero reference position of each segment obtained from a static standing trial. The error in fitting a biomechanical model to a dynamic trial is represented by the segment residual. Fitting this static model to each dynamic trial resulted in typical values of 2 – 4 mm.

The six degree of freedom kinematics of each segment were calculated for the trial with the lowest aggregate segment residual value (calcaneus: 2.0 mm, metatarsals: 2.3 mm, phalanges: 2.4 mm). The linear kinematics of each segment were calculated from the displacement of each segment origin. In agreement with ISB guidelines [14], a Cardan sequence of Y (M-L), X (A-P), Z (D-V) was found to best describe segment rotations and avoid gimbal lock. Segment rotation amplitudes were thus calculated about the lab origin using this sequence.

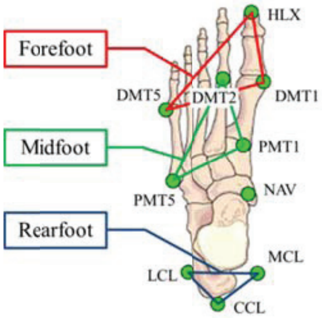

Fig. 1. Three segment foot model encompassing calcaneal, metatarsal and phalangeal segments

2.2. Finite Element Modelling

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, Germany) and transformed to match the position of the marker centre points as recorded in the first frame of the kinematic trial. The CAD geometry of the midsole and outsole were obtained from manufacturing tooling profiles and then aligned to the scan geometry in order to orientate each shoe component in the lab coordinate system at an instant immediately prior to heelstrike. Geometrical differences between the subject's foot and the last mean that perfect positioning of the footwear geometries is not achievable and a best fit must be sought. Analysis of this procedure has identified an average error of 4 mm at each marker location.

Footwear geometries were meshed with linear tetrahedral C3D4 elements using HyperMesh (Altair, USA). The target element size was selected based on the results of a mesh sensitivity analysis performed to ensure that a converged numerical solution had been achieved. Maximum vertical GRF served as the convergence criteria with the tolerance level set as a change of less than 2%. Rigid plates constructed of triangular R3D3 shell elements were created to represent the functional segments of the human foot with dimensions determined from a sagittal MR scan of the foot-ankle complex. Initial trials suggested that further constraint was required between the rigid foot segments so the geometry of a scanned foot prosthesis (Otto Bock, Germany) was introduced to the model and meshed with C3D4 elements. The assembled footstrike model is shown below in Fig. 2.

Fig. 2. a) Assembled footwear model including deformable foot instance; b) Footwear instances with rigid foot segment plates

The material model for the EVA midsole foam was characterised from uniaxial tensile, simple compression and planar shear tests performed on samples of uniform geometry. Using Abaqus 6.11 (Simulia, USA), the most appropriate representation of material behaviour under loading was found to occur with a first-order hyperfoam strain energy function. Similarly, material parameters for the blown rubber used in the shoe outsole were determined from uniaxial tension and simple compression tests. The material was best represented with a third-order hyperelastic strain energy function. A Poisson's ratio of 0.475 was defined to represent near incompressibility. The density of both materials was determined by weighing samples of known dimensions with an electronic balance.

A first-order hyperfoam 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.

The rigid plates representing the three modelled segments of the human foot were each driven independently with transient six degree of freedom displacement boundary conditions. These were applied to a rigid body reference point located at the segment origin as defined in the biomechanical model. The procedure for determining the amplitudes used in the displacement boundary conditions is described above in section 2.1. All analyses were performed with the Abaqus/Explicit solver.

3. Results

3.1. Model Validation

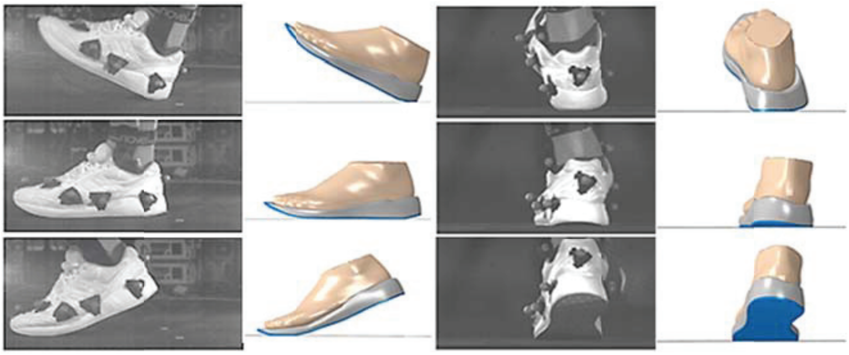

Fig. 3. Comparison of model field output to experimental HSV video footage at heelstrike, midstance and push-off

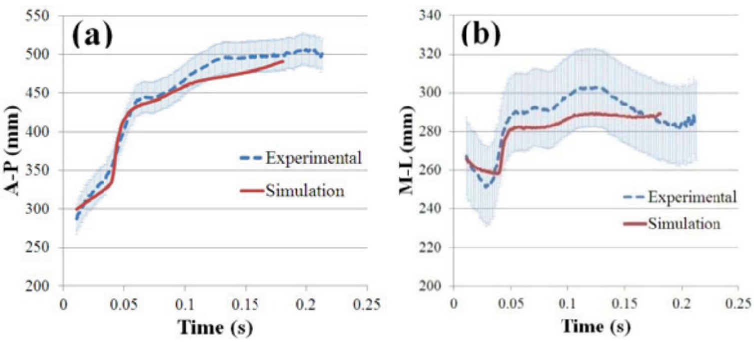

Fig. 4. Comparison of simulated and experimental COP location with experimental error tolerance of 20 mm shown [1].
(a) Anterposterior axis. (b) Mediolateral axis

Fig. 3. shows that excellent agreement was seen between model field output and high speed video footage of the corresponding biomechanical trial. Similarly, Fig. 4. shows that 92% of model COP output readings fell within an experimental error tolerance of ± 20 mm [1].

3.2. Sensitivity Analysis

Previous research found that good agreement between the simulated and experimental vertical ground reaction forces was achievable with a kinematically driven finite element footstrike model. However, it was also found that the magnitudes of the loads applied with such a modelling methodology are highly sensitive to the initial orientation of the footwear geometries [15]. To investigate the sensitivity of model COP output location to the footwear's initial orientation the position of the floor instance was altered from its base position by translating ± 2 mm vertically and by rotating ± 1° about the sagittal and frontal axes. The results of this analysis are shown below in Fig. 5.

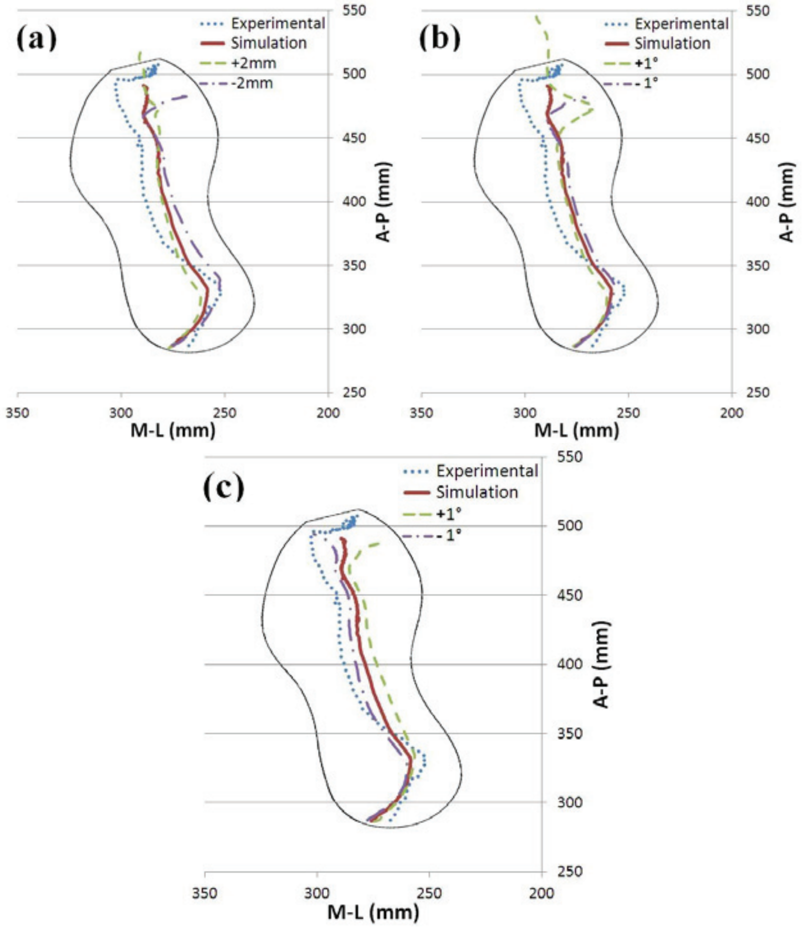

Fig. 5. Variation of COP output as a result of repositioning model floor instance. (a) Vertical translation. (b) Sagittal rotation. (c) Frontal rotation

In comparison to the base model, COP output location was found to be most sensitive to rotation about the sagittal axis with a maximum change of 69 mm. This was largely due to an extended period of contact at toe-off. Output location was altered by up to 26 mm and 19 mm for vertical translation and rotation about the frontal axis respectively.

4. 4. Discussion

The finite element footstrike modelling methodology presented in this report has been shown to provide simulated COP output locations that largely fall within an experimental error tolerance of those recorded during the corresponding biomechanical trial. However, the procedure used to determine model initial orientation relies on a best-fit procedure that has an average error of 4 mm at each marker location. In addition, the residual value associated with determining the kinematics of each foot segment was also found to be at least 2 mm. COP output has been shown to be highly sensitive to the initial positioning of footwear geometries and it is therefore significant that a rotation of only 1° resulted in a change in COP location of up to 69 mm.

The methodology presented in this report allows for complex, multiaxial loads representative of a human footstrike to be applied to a prospective footwear design and represents significant progress on previously reported finite element footstrike models. However, the demonstrated sensitivity of COP output to initial orientation raises serious concerns about the limitations of using kinematic boundary conditions to drive such a model.

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