# Developing a Finite Element Model to Investigate Second Metatarsal Stress During Running

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## Summary

Second metatarsal (2MT) stress fracture is a common and burdensome injury amongst runners, however understanding of the risk factors leading to injury is limited. Finite Element (FE) modelling represents a viable biorealistic alternative to invasive studies and simple beam theory models. This study shows the design and validation of a simple subject-specific FE model of the 2MT incorporating geometrically accurate soft tissue and loading. Results show a good comparison with both recent models and bone staple strain gauge data.

**Key Words:** *Biomechanics; Stress fracture; Finite element; Modelling*

## Introduction

Running is an excellent method of training cardiovascular fitness, which has numerous well documented health benefits. Importantly, physical fitness is strongly linked with longevity [4, 13] with regular physical activity reducing the risks of coronary heart disease, cerebrovascular disease, hypertension, type II diabetes, various cancers, and osteoporosis [8]. A recent study has suggested that physical inactivity is responsible for 6% of coronary heart disease burden worldwide, 7% of diabetes, 10% each of colon and breast cancers [9]. It has been suggested that inactivity is responsible for 9% of premature mortality and another systematic study [11] suggests that vigorous exercise and sports shows the largest reduction in all-cause mortality with moderate activities of daily living being beneficial but to a lesser extent. Any sporting activity brings with it the risk of injury, with certain injuries associated with certain types of training. For long distance runners, there is a particularly high incidence of lower limb injuries, with one systematic review finding the incidence to range from 19.4% to 79.3% across the 17 studies it included [14]. Injury is detrimental as it diminishes the pleasure derived from exercise and limits participation, sometimes for an extended period of time or may cause a permanent withdrawal from the activity. An injury of particular burden amongst runners is stress fracture injury of the 2$^{nd}$ metatarsal (2MT) bone [2, 7, 10] which may take up to 12 weeks to heal resulting in reduced activity during that time. Current understanding of the factors that may predispose an athlete to this injury is limited particularly as direct measurement of the stress in the bone during running requires invasive procedures, such as the surgical implantation of a bone staple strain gauge [10], leading to altered biomechanics during gait and confounding study results. In contrast to direct measurement, mathematical modelling has been used to estimate forces acting on the metatarsals during running or walking in several studies [7, 12] but these require many assumptions regarding geometry and cannot account for interactions between tissue types. In contrast, the finite element (FE) method has been used more recently to investigate stress distributions in the metatarsals during running [5], however, biorealistic models often have prohibitively long development, construction and run times when investigating groups of participants [1] and many simplifications are needed to produce a model that can investigate groups of participants in a realistic timeframe. Therefore the purpose of this study was to develop and validate a FE model that allows estimation of the stresses acting on the 2MT during the ground contact phase of one running step. The model incorporates subject-specific geometry and soft tissue effects, whilst minimising the complexity and therefore computing cost.

## Methods

Data were collected from eighteen (10 female) participants (age 24 ± 7.8 years; mass 64.8 ± 11.2 kg; height 1.68 ± 0.09 m). No participants reported any current injuries affecting their running regimen and no participants had sustained any lower limb injuries that prevented their normal training within the last year. Eligible participants were given information about the study and provided written informed consent. The study was given ethical approval by the Sport and Health Sciences Ethics Committee, University of Exeter.

To determine individual metatarsal geometry, magnetic resonance (MR) images were collected from each participant whilst lying supine within a 1.5 T superconducting whole body scanner (Gyroscan Intera, Philips, The Netherlands). The location of the second metatarsal and phalange was initially identified via palpation and a cod liver oil capsule placed on the foot at that location using micropore tape. The unloaded foot was then placed against a flat vertical barrier within a quadrature head coil to minimize movement, and to ensure each data set was acquired with the foot in a similar position. Stacks of MR images covering the whole of the foot and centred around the second metatarsal, as identified in the images from the high intensity cod liver oil capsule, were then acquired in sagittal, coronal and axial planes. In all cases a T1 weighted (repetition time 20 ms, echo time 4.0 ms, flip angle 500) 3D gradient echo sequence was utilised with an in-plane resolution of 0.3 x 0.3 mm and a slice thickness of 0.7 mm. Depending on the imaging orientation, between 60 and 160 slices within a stack were required for full coverage.

The participant's height and mass were measured whilst participants wore their own running kit. Synchronised kinematic, kinetic and plantar pressure data were collected during running at a constant speed of 3.6 $ms^{-1}$ along a runway using four CX1 units (Coda CX1, Codamotion – Charnwood Dynamics Ltd., U.K.) with an integrated force plate (1000 Hz) (AMTI BP400600HF, Advanced Mechanical Technology Inc., U.S.A.). 19 active skin markers (200 Hz) were attached directly to the skin and used to mark strategic bony landmarks of the foot and shank, similar to the Oxford Foot Model [3].

A separate plantar pressure plate (RSscan 0.5 m Hi-End Footscan, RSscan – Beringen, Belgium) was placed over the force plate such that the pressure plate was entirely within the boundaries of the force plate. Pressure data were collected at 200 Hz using Footscan software (RSscan Footscan Gait v7, RSscan – Beringen, Belgium). Trials were completed barefoot. An opportunity to warm up was provided and familiarisation trials were completed until the participant was comfortable running at the desired speed on the runway surface (EVA foam). Feedback on the running speed was provided after each attempt. The experimental protocol consisted of running at a constant speed ensuring that the right foot contact was within the pressure plate boundaries. A trial was considered successful when the right foot contacted the pressure plate, speed was registered as 3.6 $ms^{-1}$ (±5%), markers showed good visibility during foot contact with the pressure plate and the investigator observed no unusual movement during footplate contact. Ten successful trials were recorded per participant.

Geometrically accurate 2MT and encapsulating soft tissue geometry were recreated from MR images using ScanIP software (Simpleware ScanIP, Synopsys, CA U.S.A.), separating cortical and trabecular tissues and segmenting only the soft tissue directly surrounding the 2MT. Ground reaction force data in both the vertical and anterior/posterior direction were scaled to represent the load under the 2MT using the mapped pressure data from the pressure plate. The angle between the 2MT head and the ground was calculated from the posterior and distal 2MT markers whilst the eversion angle of the foot was calculated using the markers at the first and fifth metatarsal heads.

The model was assembled in Abaqus software (Simulia Abaqus, Dassault Systemes, France). Literature values [1, 6] were used to assign material properties to parts as described in Table 1.

| Part | Young's modulus (MPa) | Poisson's ratio |
|---|---|---|
| Cortical Bone | 17000 | 0.3 |
| Trabecular Bone | 700 | 0.3 |
| Encapsulating Soft Tissue | 1.15 | 0.49 |
| Ground Support | 50000 | 0.1 |

Table 1: Material properties of model parts

The boundaries between tissue types were modelled as a fixed encapsulation, and the interface between the foot and the ground was modelled using contact elements with a coefficient of friction equal to 0.6 [1]. Loading was applied via a ground support structure under the soft tissue, using a total force load on the relevant faces. Final assembly can be seen in Figure 1.

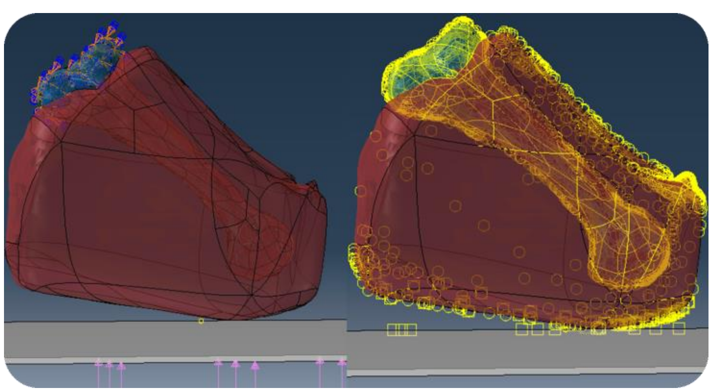

Figure 1: Wire model showing Left: boundary conditions (blue and orange arrows) and loading applied to ground support (pink arrows). Right: Soft tissue interactions (circles), floor interactions (squares)

A FE simulation was used to determine deformation of the tissues and corresponding stress patterns and magnitudes under the application of load. A mesh sensitivity analysis was conducted to ensure the stability of results and the model was validated by comparing peak contact stress between the foot and the ground to experimentally collected pressure data.

## Results and Discussion

Initial sensitivity analysis results from one participant reveal the model to be sensitive to floor element number but that it does not increase computing cost more than a few minutes, therefore a relatively high number of floor elements can be used. The encapsulating soft tissues were sensitive to an increase in element number, but an increase from 33361 to 66512 elements did not change the stress seen in other parts of the model by more than 1%. However it did greatly increase computational time, therefore the lower number was chosen. The bone was found to be sensitive to changes in element number up to 10303 elements, at which point the change in stress seen was less than 1% and the computing time increased from 110 minutes to 27 hours. Peak floor pressure seen during the simulation was 0.4368 MPa compared to 0.4745 MPa seen experimentally, a difference of 8%. A maximum stress on the dorsal surface of the 2MT of 38.03 MPa (Figure 2) was seen, equivalent to 2237 με, which compares well with both existing recent models showing median strain of 1937 με during overground running in minimalist shoes [5] and bone staple strain gauge data showing 1891 με during barefoot treadmill jogging [10]. Element sizes corresponding to this analysis were used for all other participants. Average results from all 18 participants at the time of peak ground reaction force show an average maximum stress of 29.39 MPa equivalent to 1728 με, again comparing favourably to strain gauge experimentation.

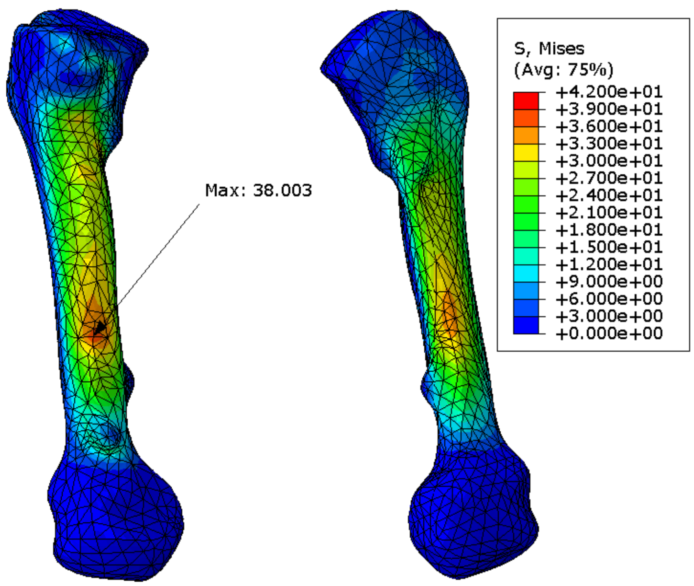


Figure 2: stress distribution (MPa) on the second metatarsal of a single participant at midstance showing maximum stress location on the dorsal surface (left) and stress distribution on the plantar surface (right).

## Conclusions

A FE model of the 2MT and surrounding soft tissues has been developed and initial results show the model to be stable and providing a good match to both experimentally collected data and previous research using models and bone strain gauge experiments in vivo.

## Acknowledgments

This work is part of a studentship that was funded by the Engineering and Physical Sciences Council (EPSRC) through the EPSRC Doctoral Training Partnership at the University of Exeter.

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