

Estimated third metatarsal bending stresses are highly susceptible to variations in bone geometry

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3 1 **Estimated third metatarsal bending stresses are highly susceptible to**
4 **variations in bone geometry**
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7 3 **Abstract**
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10 4 *Background:* Third metatarsal stress fractures are relatively common during Royal
11 Marines recruit training, however their aetiology is poorly understood. Mathematical
12 modelling of the third metatarsal may aid in understanding risk factors for stress
13 fracture, particularly if the influence of footwear on peak bending stresses can be
14 determined. This study built on previous models of metatarsal bending stress by
15 integrating individual metatarsal geometry and gait data.
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20 10 *Methods:* Data from five males with size 11 (UK) feet were acquired. MRI images
21 were digitised to determine cross-sectional bone parameters. Gait variables included
22 vertical ground reaction forces, plantar pressure and foot orientation. The magnitude
23 and location of peak bending stresses were calculated for barefoot running, before
24 standard issue combat boots and trainers were compared.
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29 15 *Findings:* Estimated peak compressive, tensile and torsional stresses were greater in
30 combat assault boots than trainers ($p < 0.05$) with medium effect sizes but wide
31 confidence intervals. However, differences in bone geometry between individuals
32 had a much greater influence on estimated peak stresses.
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37 19 *Interpretation:* Results suggest that bone geometry has a greater influence on third
38 metatarsal stress fracture risk than footwear. Future bone stress simulations should
39 account for bone geometry. Further development of the model in a variety of
40 participants should proceed to verify these suggestions.
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45 23 **Keywords:** Bone; mathematical model; stress fracture; gait; beam theory.
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47 24 1. **Introduction**
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49 25 Third metatarsal stress fractures (MT3SF) are the most common lower limb stress
50 fracture affecting Royal Marines (RM) recruits during training[1], however little is
51 known about the aetiology of this injury. Stress fractures develop where insufficient
52 remodelling occurs in response to damage sustained during repeated submaximal
53 loading. Such damage may occur due to either the characteristics of the applied load
54 (e.g. magnitude, frequency, direction) or the bone's inability to withstand it (e.g. low
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3 31 bone strength or quality). In an attempt to better understand both the internal loads
4 32 experienced by the bone, and ability of that bone to withstand it, it would be
5 33 beneficial to determine the strain acting on the bone. While direct *in vivo*
6 34 measurement techniques could be used to indicate the strain acting on bone for a
7 35 given activity, they are invasive and have many limitations. An alternative approach
8 36 is to estimate bone loading using mathematical modelling.

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14 37 The few previous studies to model bone strain have used laboratory-based
15 38 techniques to estimate external load characteristics[2], while mechanical tests[3] or
16 39 scanning techniques[4] have provided estimates of bone geometry and quality.
17 40 Arangio et al.[4] built upon earlier work focusing specifically on the fifth metatarsal[5],
18 41 in which beam theory was used to calculate stress acting on slices of a plastic mould
19 42 of the bone. Gross and Bunch[2] used inverse dynamics and beam theory to
20 43 estimate sagittal plane bending moments and subsequent bending strain acting on
21 44 the metatarsals during gait. These authors used reference data for bone
22 45 characteristics and represented the metatarsals as simple uniform ellipses while only
23 46 estimating strain at the midpoint of the metatarsal. Despite the important work of
24 47 Gross & Bunch[2] and Arangio et al.[4], no research has combined individual bone
25 48 geometry, orientation and external load data to estimate MT3 bone stress during
26 49 locomotion. The development of such a model of bone loading may significantly
27 50 advance the understanding of MT3SF aetiology.

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38 51 Footwear can influence the loading of the forefoot and thus potentially MT3SF risk.
39 52 At the time of testing RM recruits were issued with a gym trainer (GT), used heavily
40 53 in the early weeks of training, and a combat assault boot (CAB), phased in for most
41 54 exercises by week 8 of training. This footwear has been assessed previously in
42 55 regard to MT3SF aetiology[6], with the authors suggesting the CAB would be
43 56 expected to cause greater risk of MT3SF than the GT, primarily due to increased
44 57 forefoot loading. It would be beneficial if a model could be developed to accurately
45 58 assess loads when running in these different footwear conditions, although an initial
46 59 barefoot assessment is necessary for development of an accurate model.

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54 60 Therefore, the aims of this study were to 1) develop a model of the MT3 using
55 61 accurate, subject-specific anatomical data combined with external loading data and
56 62 2) apply the model to the comparison of MT3 loading during running in the GT and

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3 63 CAB. Stage 1 was the development of a model to estimate bending stress acting on
4 64 the MT3 during barefoot running. This model would improve on previous attempts in
5 65 the literature through the use of participant-specific bone geometry, plantar loading
6 66 and kinematic data for running. Stage 2 was to apply the model to the comparison of
7 67 peak bending stresses in the MT3 during running with standard issue GT and CAB.
8 68 For Stage 2, it was hypothesised that peak MT3 bending stresses would be greater
9 69 in the CAB than the GT.
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18 71 2. Methods

20 72 2.1. *Participants*

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23 73 Five male participants (age: mean 18.8 SD 0.83 yrs; mass: mean 79.8 SD 2.28 kg)
24 74 from a cohort of undergraduate sports science students volunteered to take part in
25 75 the study. All volunteers were heel-toe runners with size 11 (UK) feet, familiar with
26 76 wearing and running in military boots through participation in the University Officer
27 77 Training Corps. The study was given ethical approval by the Sport and Health
28 78 Sciences Ethics Committee with all participants free from contraindications to
29 79 undergoing MRI scans.
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35 80 2.2. *MRI data*

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38 81 Cod-liver oil markers provided reference points for identifying the MT3 during MRI
39 82 scanning due to their high visibility in images. With the participant lying supine, their
40 83 right foot was prepared with cod-liver oil markers[7], secured using masking tape in
41 84 the following locations: dorsal aspect of the proximal end of the MT3 (articulation
42 85 with the lateral cuneiform); dorsal aspect of the distal end of the MT3 (third
43 86 metatarsophalangeal joint); medial aspect of the articulation of the first
44 87 metatarsophalangeal joint, lateral aspect of the articulation of the fifth
45 88 metatarsophalangeal joint. Marker placement locations were estimated by palpation
46 89 of the foot, and verified by subsequent observation of the MRI scans.
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54 90 After preparation with markers, the participant's right foot was fixed to a rigid plastic
55 91 block with Velcro ties so that the ankle was kept at approximately a 90 degree angle,
56 92 and the plantar aspect of the foot was in contact with a surface. The scanned section
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3 93 was defined with respect to the axes of the foot, using marker reference points.
4 94 Scans were obtained at 5 mm intervals in three planes relative to the foot: sagittal,
5 95 transverse and frontal. Sample images are presented in Figure 1.
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11 97 The following MRI scan sequences were used to obtain images in each plane. For
12 98 the frontal plane scan a turbo spin echo sequence (echo time 20 ms, repetition time
13 99 500 ms, averaged over 4 acquisitions) was used with 0.5 x 0.7 mm in-plane
14 100 resolution and 16 slices of 3 mm thickness acquired. For the transverse plane a T1
15 101 weighted gradient echo sequence was employed (echo time 25 ms, a repetition time
16 102 20 ms, averaged over 2 acquisitions) with in-plane resolution of 1.0 x 1.1 mm, and
17 103 50 slices of 2.5 mm thickness acquired. For the sagittal scan a turbo spin echo
18 104 sequence (echo time 20 ms, repetition time 500 ms, averaged over 3 acquisitions)
19 105 was used with 0.5 x 0.6 mm in-plane resolution and 16 slices of 3 mm thickness
20 106 acquired.
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29 107 Frontal plane scans were converted from raw DICOM images to AVI clips using
30 108 ImageJ software (v. 1.46r, National Institutes of Health, USA). Images were
31 109 concatenated in sequence (proximal to distal) and converted to an AVI clip before
32 110 being digitised in AVI Digitiser (RF Spectrum Modelling, UK). AVI Digitiser allows
33 111 sub-pixel digitising using image interpolation, providing high levels of precision.
34 112 Ninety-six locations were digitised, 32 of the inner surface of the bone, and 64 of the
35 113 outer surface. In order to promote even spacing of digitised locations, points were
36 114 digitised in sequence, as demonstrated by the schematic in Figure 2(A). After
37 115 digitising, 2D coordinates for each point were exported and used to define 96
38 116 irregular triangles (Figure 2(B)) from which the area and cross sectional moment of
39 117 inertia of each slice were determined. The area of each triangle was calculated using
40 118 Heron's formula and summed to give the cross-sectional area of each slice (CA).
41 119 The vector length between the centroid of each triangle and the centroid of the slice
42 120 was used to calculate the moment of inertia about the horizontal (I_{xx}) and vertical (I_{yy})
43 121 axes for each slice.
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56 123 *2.3. Dynamic gait data*
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3 124 The collection of shod gait data has been described previously (Nunns et al., 2012).
4 125 The collection of barefoot (BF) data differed only in that a pressure plate sampling at
5 126 500 Hz (0.5 m long, 4096 sensors, RSScan, Belgium) was used instead of an in-
6 127 shoe pressure insole device. In the BF condition, the pressure plate was set above a
7 128 force plate (AMTI, Watertown, MA, USA) flush within a 9 mm thick EVA runway with
8 129 a Shore A rating of 40, measured with a durometer (Durotech, model B202,
9 130 Hampden Test Equipment Ltd., England). Participants performed several habituation
10 131 trials to allow them to adopt their typical foot strike modality[8]. In the shod
11 132 conditions, participants ran over the laboratory floor, ensuring their right foot struck
12 133 the force plate.

13 134 Two-dimensional kinematic data were collected using an eight camera system
14 135 (Vicon Peak, 120 Hz, automatic, optoelectronic system; Peak Performance
15 136 Technologies, Inc., Englewood, CO) and interpolated to 500 Hz to match loading
16 137 data. Markers were placed at the following locations in order to determine the three-
17 138 dimensional orientation of the foot: superior posterior calcaneus; inferior posterior
18 139 calcaneus; inferior lateral calcaneus; lateral malleolus; dorsal aspect of the proximal
19 140 end of the MT3; dorsal aspect of the distal end of the MT3; medial aspect of the
20 141 articulation of the first metatarsophalangeal joint, lateral aspect of the articulation of
21 142 the fifth metatarsophalangeal joint.

22 143 The angle of MT3 inclination indicated by dorsal skin markers was verified against
23 144 the MRI scan for each individual. The sagittal plane angles provided by the cod-liver
24 145 oil capsules, the midline of the MT3 shaft and the sole of the foot were measured
25 146 and compared. The results of this analysis (Table 1) indicate that markers represent
26 147 the angle of inclination of the MT3 to within an average of 0.04 (SD 3.2 degrees,
27 148 range 8.2 degrees). For the analysis of shod running, the shoe upper prevented
28 149 accurate placement of markers. Therefore, using the data from Table 1, the foot
29 150 angle (determined by skin markers) was corrected using the relevant bone angle for
30 151 each participant to give MT3 inclination angle.

31 152 The external load acting on the MT3 was assumed to be applied beneath the MT3
32 153 head. Estimation of vertical load at this location was performed using mask analysis
33 154 within the Footscan Insole (version 2.39, RSScan, Belgium) or Footscan Gait
34 155 (version 7, RSScan, Belgium) software respectively. For each participant the sagittal

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3 156 plane image best showing the plantar surface of the metatarsal heads was digitised
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5 157 to provide the location of the centre of the MT3 head relative to the cod-liver oil
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7 158 markers, and the length of the MT3. These markers corresponded to the placement
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9 159 of foot markers during running data collection. For each trial, the central point of the
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11 160 mask (area 3.4 cm²) for the MT3 head was placed at the centre of the MT3 head,
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13 161 using these coordinates. Vertical force data for this mask location were exported
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15 162 from the pressure software and scaled to vertical force data obtained simultaneously
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17 163 from the force plate, using peak active force as a reference[9].
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19 2.4. Model development

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21 166 The model considered the MT3 as a cantilever fixed at the proximal end, with the
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23 167 distal end being free and point-loaded. For each cross-section of the bone, three
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25 168 axes originating from its centroid were defined. The x-axis was horizontal, the y-axis
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27 169 was vertical and the z-axis was parallel to the longitudinal axis of the bone. In a
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29 170 similar approach to that of Milgrom et al.[3] when modelling the tibia, bending
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31 171 stresses at the cross-section of the MT3 were calculated relative to the x-axis and
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33 172 the y-axis. Torsional stress was calculated about the z-axis.

34 173 At any cross section of the metatarsal, the bending moment can be determined by
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36 174 equation 1:

$$37 \quad 38 \quad 39 \quad 40 \quad 41 \quad 42 \quad 43 \quad 44 \quad 45 \quad 46 \quad 47 \quad 48 \quad 49 \quad 50 \quad 51 \quad 52 \quad 53 \quad 54 \quad 55 \quad 56 \quad 57 \quad 58 \quad 59 \quad 60$$

$$175 \quad M_{be} = F(L - x) \quad \text{Eq. 1}$$

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177 Where F is the applied force; L is the length of the metatarsal and x is the
178 perpendicular distance from the section to the point of load application. Tensile
179 stress, compressive stress and axial stress equations are displayed below:

$$180 \quad \sigma_{ax} = \frac{F}{A} \quad \text{Eq. 4.3}$$

$$181 \quad \sigma_c = \sigma_{ax} + \sigma_{be} \quad \text{Eq. 4.4}$$

$$182 \quad \sigma_t = \sigma_{ax} - \sigma_{be} \quad \text{Eq. 4.5}$$

183 where σ_{ax} is axial stress; σ_c is compressive stress; σ_{be} is bending stress; σ_t is tensile
 184 stress; F is the force applied and A is the cross-sectional area of the bone. In order
 185 to determine maximal σ_{be} the following general equations were used:

$$\sigma_{be}(\text{about } x\text{-axis}) = \frac{(M_{be} \cdot y)}{I_x} \quad \text{Eq. 4.6}$$

$$\sigma_{be}(\text{about } y\text{-axis}) = \frac{(M_{be} \cdot y)}{I_y} \quad \text{Eq. 4.7}$$

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 191 where y is the maximal distance of the cross section from the neutral axis in the
 192 relevant direction and I_x or I_y is the area moment of inertia about the neutral axis in
 193 the relevant direction. Maximal torsional stress was calculated using the following
 194 equation:

$$\sigma_{tor} = \frac{(M_{be} \cdot R)}{I_z} \quad \text{Eq. 4.8}$$

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 197 where I_z is the polar moment of inertia about the neutral axis, and is the sum of I_x
 198 and I_y and R is the radius of the outer surface of the bone. R was the mean of the
 199 radial distances of the outer 64 points from the centroid. For each cross-sectional
 200 slice of the MT3 of each participant, the use of the equations above provided data for
 201 the three stresses σ_{ax} , σ_t , and σ_c . Figure 3 is a mechanical diagram of the model.

202 For each stress category, the magnitude and location of peak stress was identified.
 203 All calculations were performed using custom Matlab scripts (v.2008b, The
 204 Mathworks Inc, USA). Peak compressive, tensile and torsional stresses under
 205 vertical loading were compared between the CAB and GT conditions using Wilcoxon

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3 206 tests in SPSS (v.21, IBM, USA) using an alpha level of 0.05. Effect sizes with 95%
4 207 confidence intervals (95% CI) were calculated (Cohen's d [10]) with a medium effect
5 208 size considered to be .50.
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11 210 3. Results

13 211 3.1. *Stage 1 results – barefoot running*

16 212 Table 2 summarises the area and location of the slice of metatarsal with the
17 213 maximum and minimum cross-sectional areas (CA) in each participant. The location
18 214 of minimum area was also the location of maximum axial stress. In four cases the
19 215 minimum area was in the slice adjacent to the distal slice, with participant 4 also
20 216 having a low CA at a distal location. Mid-point and minimum CA were similar
21 217 between participants, however large variation was seen in the maximum CA.
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27 218 The mean magnitude and timing of peak plantar force are included in Table 3, in
28 219 addition to the times of heel off and peak stress. Heel-off always preceded peak
29 220 force, with peak stress and peak force occurring at similar times. All timings are
30 221 presented as % of stance time.
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34 222 Table 4 shows the mean peak compressive, tensile and torsional stresses, and their
35 223 locations, for each participant. Table 5 indicates the stress values for the mid-point of
36 224 the metatarsal.
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40 225 3.2. *Stage 2 results – shod running*

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42 226 Table 6 summarises the peak plantar force beneath the MT3 in each condition,
43 227 which was greater in the CAB for each recruit ($p < 0.05$). All peak stresses were
44 228 significantly greater in the CAB than the GT, with a medium effect size reported
45 229 (Table 7), although wide 95% CIs reflect the uncertainty in these effects for all
46 230 footwear comparisons.
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51 231 4. Discussion

52 232 The present study is the first to incorporate individual geometry and individual
53 233 kinematic and kinetic data into a model of MT3 loading, therefore providing the
54 234 opportunity to investigate the influence of variations in these factors on MT3 bending
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3 235 stresses during gait. Axial, bending and torsional stresses were estimated along the
4 236 MT3 of the right foot of five males during running, using a simple model based on
5 237 beam theory. The model was applied initially during barefoot running, and then when
6 238 shod in the RM recruit standard issue CAB and GT. In partial support of the
7 239 hypothesis, it was observed that wearing the CAB resulted in statistically significantly
8 240 greater estimated stresses than wearing the GT, although the small sample size
9 241 used to pilot this application of the model led to imprecision in the estimates, as
10 242 reflected by wide confidence intervals. Variation in the geometric properties of the
11 243 MT3, even within a sample of individuals with the same foot size, led to much larger
12 244 variation in estimated peak bending stresses. These findings support the inclusion of
13 245 individual bone geometry data in future metatarsal simulation models.

246 *4.1. Influence of bone geometry*

247 Examination of the locations of maximum stress and minimum CA highlight the
248 importance of bone geometry, in particular its distribution about the centroid and its
249 position relative to the point of load application in determining its resistance to
250 bending. Although the lowest CA of each metatarsal was at the distal end, peak
251 stresses occurred at much more proximal locations, within the middle five slices of
252 the metatarsal, despite the systematic increase in bending moment with each more
253 proximal slice of the metatarsal. Variations in bone geometry may lead to regions of
254 high stress at certain 'hot spots' on the metatarsal. As such, future research should
255 avoid the use of arbitrary bone geometry when estimating bending stresses. This is
256 further supported by the large range of estimated peak stresses determined despite
257 participants having the same shoe size and MT3 lengths within a range of 13 mm.

258 Peak tensile stresses differed by 19 MPa, equivalent to approximately 1100 $\mu\epsilon$, in
259 MT3s 2 and 4, which were 3 mm different in length, 10 N in peak force. Such
260 variation of peak stress within a relatively homogeneous group suggests estimations
261 of internal loading may be erroneous without knowledge of MT3 geometry. It should
262 be noted that peak stresses are strongly influenced by the maximum distance of any
263 digitised point from the centroid of the slice. Reliability assessment of the model[11]
264 reports very low variation (CV% below 3.45%) between three repeat analyses of the
265 same participant, suggesting that digitisation reliability was high. Further examination
266 of data could provide mean stresses, or stresses at set azimuthal intervals, which

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3 267 may be less sensitive to variations in geometry. However, if wishing to estimate peak
4 268 bending stresses, the current results indicate that the use of reference geometry
5 269 data (e.g. in [2]) in order to compare between individuals is not supported.
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10 11 271 4.2. *Influence of footwear*

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13 272 Shod running data indicated greater peak bending and torsional stresses in the CAB
14 273 compared to the GT ($P<0.05$), although the 95% confidence intervals suggest
15 274 uncertainty over this effect. While a small and under-powered sample was used to
16 275 test the application of the model, it is noted that for each individual, stresses were
17 276 greater in the CAB than the GT. Table 6 also shows consistently greater peak
18 277 ground reaction forces in the CAB than the GT for all individuals. It is therefore
19 278 suggested that differences in localised force beneath the MT3 likely explain
20 279 differences in peak bending and torsional stresses between the two conditions
21 280 (Table 6). Our research group has previously observed increased forefoot loading in
22 281 the CAB compared to GT [6]. Sensitivity analysis of the model showed that maximal
23 282 compressive stress increased by around 0.6 MPa per Newton of added force [11].
24 283 This therefore suggests that increased plantar loading, specifically at the forefoot
25 284 during running in the CAB may lead to the observation of increased MT3 bending
26 285 stresses. Further investigation of these suggestions in a larger sample is required to
27 286 determine specific mechanisms for increased stress fracture risk with changes in
28 287 footwear.

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32 288 Given the observation that increased external loading beneath that MT3 head
33 289 increases MT3 bending stress, strategies to reduce MT3 stress fracture risk should
34 290 look to reduce plantar loading. This variable can be influenced by footwear
35 291 interventions. Windle et al.[12] observed that cushioning insoles reduced plantar
36 292 pressures at the heel and forefoot in the RM recruit population. The efficacy of
37 293 cushioning insoles in reducing metatarsal stress fracture risk in particular is not
38 294 guaranteed however, as this type of injury was not significantly reduced in the RM
39 295 recruit population when such insoles were prescribed[13]. This may be because an
40 296 increase in contact area associated with cushioning insoles will reduce plantar
41 297 pressure but not necessarily force beneath the metatarsal. A forefoot off-loading
42 298 device may be more effective in reducing MT3 loads. 'Rocker-bottom' soles[14, 15]

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3 299 and custom orthotics[16] have been shown to reduce forefoot loading in diabetic
4 300 populations, redistributing plantar loads to other areas of the foot. Research is
5 301 needed to investigate the efficacy of such devices when integrated into military
6 302 footwear, including assessment of whether risk of other injuries is increased by
7 303 redistribution of load.

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12 304 Barefoot data reveal that peak force and peak stress occurred at similar times during
13 305 stance, with both events occurring well after heel off, however this relationship was
14 306 not present in the shod conditions. Further evidence is required to understand
15 307 whether footwear can influence the timings of peak stresses at the MT3, particularly
16 308 if these are associated with increased stress fracture risk. Earlier heel off associated
17 309 with equinus deformity has been suggested to cause earlier and greater loading of
18 310 the forefoot, increasing risk of metatarsal stress fracture[17]. The results for barefoot
19 311 running highlight that peak bending stresses occur subsequent to heel off.

25 312 4.3. *Limitations*

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29 313 There are several limitations which should be acknowledged when interpreting the
30 314 findings of this study. First, the model did not take into account surrounding
31 315 structures, muscular attachment or the plantar fascia. Torsional forces, transmitted
32 316 due to the relative rotation of the forefoot and rearfoot, were not estimated. Pohl et
33 317 al.[18] reported up to 10 degrees of coupling between these foot segments during
34 318 running, which may significantly affect bone loading. Gross & Bunch[2] accounted for
35 319 the influence of toe forces at the metatarsophalangeal joint, as well as the influence
36 320 of the plantar attachment of the tibialis posterior. The contribution of the tibialis
37 321 posterior was estimated in their model[2], with this muscle playing an important role
38 322 in reducing bending stress acting on the metatarsals[19, 20]. The role of plantar
39 323 musculature should be considered in future, but in order to achieve meaningful data,
40 324 the location and transmitted force should be accurately modelled in individual cases.
41 325 Similarly, the effects of the posteriorly-directed tension caused by the attachment of
42 326 the plantar fascia to the base of the metatarsal heads should be considered. A model
43 327 of plantar fascia release by Gefen [21] suggests that the importance of this structure
44 328 in influencing metatarsal bending moments is significant.

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49 329 Although the model developed in this study has not been directly validated, the
50 330 estimated loading values can be compared with those in the literature. The mean
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3 331 peak compressive stress value reported for barefoot running was 114.43 Pa which, if
4 332 a Young's modulus of 17 GPa is assumed (as in [2]), yields a peak strain of 6749 $\mu\epsilon$.
5 333 Gross & Bunch [2] reported mean peak strain at the MT3 to be 5160 $\mu\epsilon$, despite
6 334 reporting greater mean peak plantar force than the present study (200 N compared
7 335 with 147 N). *In vivo* second metatarsal strain data have been reported during walking
8 336 to reach around 2000–2500 $\mu\epsilon$ [20, 22-25]. There are no published data for *in vivo*
9 337 MT3 strains during walking or running to which comparison could be made.
10 338 However, second metatarsal strains have been modelled to be greater than the
11 339 MT3[2], and the transition from walking to jogging has been shown to double the
12 340 observed MT2 strains[24]. Therefore in line with the estimations of Gross & Bunch[2]
13 341 it is feasible that strains in the range of 3500 to 5000 $\mu\epsilon$ could be expected on the
14 342 shaft of the MT3 depending on running speed, however the upper range is below the
15 343 predictions of the current model. These predictions need to be verified with future
16 344 work as it is recognised that simplifications of the current model will lead to over-
17 345 estimation of peak MT3 bending loads. Without suitable detailed information on
18 346 muscle forces and attachments (for example), integrating further estimations into the
19 347 model would be inappropriate.

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21 348 It was assumed that throughout stance the MT3 retained the orientation obtained
22 349 during MRI scanning, and any rotation of the MT3 relative to the vertical force vector
23 350 was ignored. This assumption will lead to errors when estimating the vertical and
24 351 horizontal distances of the cortical wall from the centroid during stance (variable 'y' in
25 352 the stress calculations). Given the elliptical nature of the MT3, rotation out of the
26 353 assumed position may lead to changes in y of a few mm. For a hypothetical mid-
27 354 shaft slice with a bending moment of 4.5 N.m (150 N force, 0.03 m moment arm) and
28 355 an inertial value about the x-axis of 150 mm⁴, a change in y from 3 mm to 4 mm
29 356 would result in a change in bending stress of 30 MPa. Estimations of peak bending
30 357 stresses are therefore most applicable to a foot position identical to that in which the
31 358 MRI scans were taken. To improve this aspect of the model, the axial rotation of the
32 359 MT3 should be tracked during gait and the relevant rotation of cross-sectional bone
33 360 coordinates performed. However, technology is not widely available to achieve this
34 361 goal, as skin mounted markers are not capable of accurately tracking bone rotations
35 362 deep within the foot.

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3 363 Horizontal forces were not integrated into the model. There is evidence that
4 364 horizontal forces may be of importance in the aetiology of MT3SF[4, 6, 26], however
5 365 effective integration of horizontal loads into the model would require knowledge of
6 366 the location, magnitude and direction of the resultant horizontal force vector relative
7 367 to the MT3; estimation of the damping of this force before it reaches the MT3 head;
8 368 and the relative ab-adduction of the forefoot with regard to the rearfoot. Such
9 369 considerations could be implemented in future iterations.

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15 370 Predicted bone strain could be validated in a larger sample using bone-mounted
16 371 strain gauges either in vivo or in cadaver feet, however this was beyond the scope of
17 372 the present research study. The application of beam theory has been demonstrated
18 373 in important previous biomechanical models of long bone bending stresses
19 374 (e.g.[2,3]). As an alternative, a finite element modelling (FE) approach could
20 375 implement a mesh analysis technique, such as the one used in Brassey et al.[27] to
21 376 more accurately determine stress across the entire surface of the bone, accounting
22 377 for factors such as the curvature of the mid shaft. While potentially more accurate
23 378 however, FE modelling is computationally more demanding. The present model
24 379 therefore provides a valuable step towards accurate estimation of metatarsal
25 380 bending stresses, in lieu of robust studies utilising strain gauge data.

381 5. Conclusion

382 This was the first model to utilise both individual geometry and dynamic gait data to
383 estimate third metatarsal axial, bending and torsional stresses when running, and we
384 performed a preliminary test of the model for running barefoot and in standard issue
385 military footwear. Results indicate the importance of plantar loading and, in
386 particular, individual bone geometry in determining the magnitude of peak stresses.
387 The variation in geometry even between a relatively homogenous group of
388 individuals may be the dominant factor in determining whether the levels of stress
389 experienced are potentially damaging. Footwear adaptations which facilitate a
390 reduction in forefoot plantar loading may be effective in reducing damaging loads.
391 However, when comparing data between individuals, inferences about internal
392 metatarsal strain based on external load data may be highly inaccurate unless
393 knowledge of the bone geometry is obtained. The present model provides an

394 opportunity to estimate MT3 bending stresses with consideration of individual
395 geometry and external loading.

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397 6. Conflict of interest statement.

398 The authors confirm there is no conflict of interest to declare.

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56 485 Tables
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486 Table 1. Inclination of the MT3 as determined by cod-liver oil capsules and the shaft
 487 of the bone. Individual angles are the mean of three measurements, are presented in
 488 degrees and represent the relative angle between the MT3 and the sole of the foot.
 489 The differential represents the extent to which the marker angle overestimates MT3
 490 bone inclination. Metatarsal length (mm) is also included for reference. The group
 491 mean (SD) is presented for all variables.

Participant	Marker angle	Bone angle	Differential	Metatarsal length
1	21.5	23.8	-2.3	69
2	21.6	20.4	1.2	73
3	24.0	23.3	0.7	63
4	19.3	21.3	-4.0	76
5	27.9	23.7	4.2	71
Mean (SD)	22.9 (3.3)	22.5 (1.6)	-0.04 (3.2)	70.3 (4.9)

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493

494 Table 2. The cross-sectional area (CA) at the minimum, maximum and mid-point
 495 locations of each individual's third metatarsal, and the magnitude and location of
 496 peak axial stress are displayed. Mean (SD) values for the group are also presented.
 497 Locations are the distance from the most distal aspect of the 3rd metatarsal head.

Participant	Min CA (mm ²)	Location (mm)	Max CA (mm ²)	Location (mm)	Mid CA (mm ²)	σ_{ax} (MPa)	Location (mm)
1	22.66	5	83.77	70	38.69	5.41 (1.94)	5
2	28.73	5	176.26	70	39.65	4.71 (1.33)	5
3	30.96	5	65.65	0	38.65	4.89 (1.76)	5
4	32.46	15	94.73	65	46.19	4.09 (1.14)	15
5	27.05	5	66.06	50	47.70	6.57 (2.39)	5
Mean	28.37	-	97.29	-	45.54	5.13	-
(SD)	(3.81)	-	(45.83)	-	(4.31)	(0.93)	-

498 σ_{ax} = axial stress.

499

500 Table 3. The mean (SD) of ten trials of the peak plantar force, time of peak force,
 501 time of heel off and time of peak stress is shown for each participant during the
 502 stance phase of barefoot running. The mean (SD) values for the group are also
 503 included.

Participant	Peak force (N)	Time of peak force (%)	Time of heel off (%)	Time of peak stress (%)
1	128.99 (42.21)	58.76 (2.01)	50.11 (1.85)	56.67 (2.12)
2	135.57 (31.09)	57.09 (1.06)	48.55 (1.57)	58.21 (3.89)
3	151.54 (54.58)	58.37 (2.83)	51.63 (2.26)	56.58 (3.67)
4	145.80 (53.97)	57.79 (1.93)	43.40 (1.54)	54.89 (2.31)
5	173.65 (68.86)	63.39 (3.55)	55.17 (1.80)	61.87 (7.84)
Mean	147.11	59.08	49.77	57.64
(SD)	(17.23)	(2.49)	(4.32)	(2.64)

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505

506 Table 4. The mean (SD) of ten trials of the magnitude and location (mm from the
 507 most distal aspect of the 3rd metatarsal head) of peak vertical compressive and
 508 tensile stresses and peak torsional stress for the right foot third metatarsal of each
 509 participant during barefoot running. Mean (SD) peak stress values for the group are
 510 also presented. Tensile stresses are negative.

Participant	σ_c (MPa)	σ_t (MPa)	Location (mm)	σ_{tor} (MPa)	Location (mm)
1	138.73 (35.36)	-132.88 (33.82)	45	68.83 (17.53)	35
2	106.41 (31.45)	-100.43 (29.78)	50	48.12 (14.24)	50
3	115.18 (42.63)	-108.70 (40.27)	25	57.06 (21.13)	35
4	77.35 (22.16)	-72.23 (20.78)	30	34.76 (9.98)	30

5	134.49 (63.01)	-125.41 (58.85)	35	62.05 (29.09)	35
Mean	114.43	-107.43	-	54.16	-
(SD)	(24.66)	(23.77)	-	(13.22)	-

511 $\sigma_c =$ compressive stress; $\sigma_t =$ tensile stress; $\sigma_{tor} =$ torsional stress.

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516 Table 5. The mean (SD) of ten trials of the magnitude of peak axial, compressive,
 517 tensile and torsional stresses at the metatarsal mid-point for each participant whilst
 518 running barefoot. Mean (SD) values for the group are also presented.

Participant	σ_{ax} (MPa)	σ_c (MPa)	σ_t (MPa)	σ_{tor} (MPa)
1	3.17 (1.14)	138.15 (35.21)	-129.38 (31.84)	68.83 (17.53)
2	3.42 (1.08)	88.58 (24.73)	-86.90 (25.78)	42.20 (11.69)
3	3.65 (1.32)	110.96 (41.07)	-103.73 (38.44)	53.89 (19.96)
4	2.00 (0.71)	71.03 (20.28)	-65.52 (18.79)	33.74 (9.65)
5	3.64 (1.44)	117.70 (50.44)	-111.26 (52.22)	52.86 (24.78)
Mean	3.18	105.28	-99.36	50.30
(SD)	(0.69)	(26.07)	(24.30)	(13.25)

519 $\sigma_{ax} =$ axial stress; $\sigma_c =$ compressive stress; $\sigma_t =$ tensile stress; $\sigma_{tor} =$ torsional stress.

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521

522 Table 6. The mean (SD) of ten trials of the peak plantar force, time of peak force,
 523 time of heel off and time of peak stress is shown for the right third metatarsal of each
 524 participant whilst running in the combat assault boot (CAB) and gym trainer (GT).
 525 The group mean (SD) is also included.

Participant	Peak force (N)		Time of peak force (%)		Time of heel off (%)		Time of peak stress (%)	
	CAB	GT	CAB	GT	CAB	GT	CAB	GT
1	161.11 (14.76)	128.56 (10.70)	51.78 (2.32)	58.20 (4.62)	56.00 (4.18)	47.60 (3.41)	60.66 (3.56)	60.69 (3.48)
2	144.13 (13.34)	125.58 (18.48)	55.20 (2.91)	57.51 (1.04)	62.10 (2.41)	60.17 (1.23)	66.64 (2.16)	64.67 (5.24)
3	165.34 (11.97)	133.11 (16.95)	63.07 (4.12)	66.57 (3.32)	68.43 (2.67)	52.98 (1.99)	67.84 (2.35)	67.78 (4.07)
4	150.23 (16.55)	115.48 (1.46)	55.66 (1.48)	57.97 (2.84)	56.29 (3.17)	55.37 (3.01)	56.60 (2.07)	60.93 (9.32)
5	133.78 (13.50)	113.64 (11.63)	70.75 (4.12)	68.07 (5.96)	70.49 (3.35)	69.30 (6.80)	59.06 (3.83)	66.96 (4.92)
Mean	150.92	123.27	59.29	61.66	62.66	57.08	62.16	64.20
(SD)	(12.77)	(8.42)	(7.61)	(5.20)	(6.71)	(8.19)	(4.88)	(3.30)

526

527

528 Table 7. The mean (SD) of ten trials of the magnitude of peak vertical compressive
529 and tensile stresses and peak torsional stress for each participant whilst wearing the
530 combat assault boot (CAB) and gym trainer (GT). Mean (SD) peak stress values for
531 the group are included. The results of a Wilcoxon paired tests are presented in the
532 bottom row, with effect size (Cohen's *d*) and 95% CI included.

Participant	σ_c (MPa)		σ_t (MPa)		σ_{tor} (MPa)	
	CAB	GT	CAB	GT	CAB	GT
1	181.20 (12.22)	141.00 (14.90)	-173.62 (12.05)	-135.21 (14.36)	89.44 (6.56)	70.00 (7.42)
2	120.10 (12.23)	109.30 (16.44)	-113.81 (11.61)	-103.65 (16.58)	54.42 (5.55)	49.54 (7.47)
3	117.00 (10.37)	92.54 (19.23)	-109.90 (9.87)	-88.04 (18.06)	57.81 (5.16)	46.27 (9.50)
4	79.10 (5.34)	60.59 (4.37)	-73.71 (5.00)	-55.81 (4.70)	37.84 (2.56)	28.99 (2.09)
5	78.14 (9.52)	61.72 (8.13)	-71.79 (9.12)	-53.75 (7.62)	36.08 (4.40)	28.42 (3.76)

Mean	115.11	93.03	-108.67	-87.29	55.11	44.64
(SD)	(42.01)	(33.91)	(41.32)	(34.21)	(21.49)	(17.16)
<i>P</i>	.022*		.022*		.022*	
(<i>d</i> [95% CI])	(.58 [-0.71 to 1.83])		(.56 [-0.72 to 1.81])		(.54 [-0.74 to 1.79])	

533 $\sigma_c = \text{compressive stress}; \sigma_t = \text{tensile stress}; \sigma_{tor} = \text{torsional stress}.$

534

535 Figure captions

536 Figure 1. Sample images of the third metatarsal of the right foot of one male
 537 participant. Top: frontal plane view of mid-section; middle: transverse (plantar) view;
 538 bottom: sagittal plane view, showing cod-liver oil skin markers.

539

540 Figure 2. A) Schematic of digitised points. Numbers represent the order in the
 541 sequence in which the point was digitised. B) The 96 triangles used in the calculation
 542 of cross-sectional area and moment of inertia. For one example triangle, the distance
 543 from the slice centroid (circle) to the triangle centroid (dashed circle) is highlighted,
 544 as used in the calculation of the cross-sectional moment of inertia.

545

546 Figure 3. Schematic showing the inputs and measurements considered in the model.
 547 (a) Displays the free-body representation of the third metatarsal, in which the axially-
 548 directed dashed line (← - -) represents the line of axial stress; θ = angle of
 549 inclination of metatarsal to the ground; F = vertical force obtained from pressure
 550 data; L = length of metatarsal; x = perpendicular distance of slice from point of force
 551 application; the thick black intersection represents a sample slice taken from the mid-
 552 shaft. This slice is depicted from a frontal perspective in (b), where X = Centroid of
 553 slice; R = radius of outer surface of metatarsal. The axes about which bending stress
 554 moment arms (γ) and inertial properties are calculated are also identified.

555

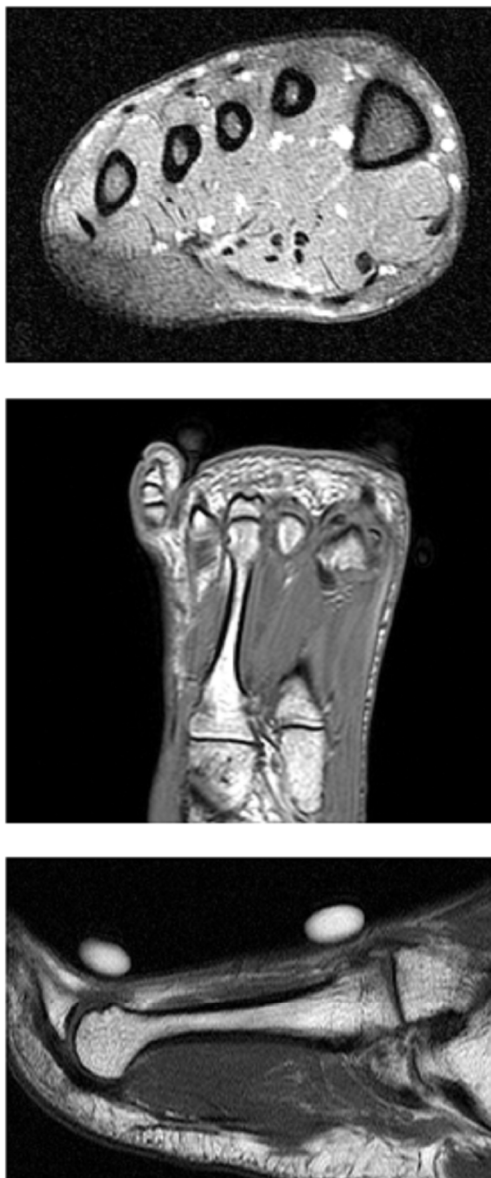


Figure 1. Sample images of the third metatarsal of the right foot of one male participant. Top: frontal plane view of mid-section; middle: transverse (plantar) view; bottom: sagittal plane view, showing cod-liver oil skin markers.

211x496mm (96 x 96 DPI)

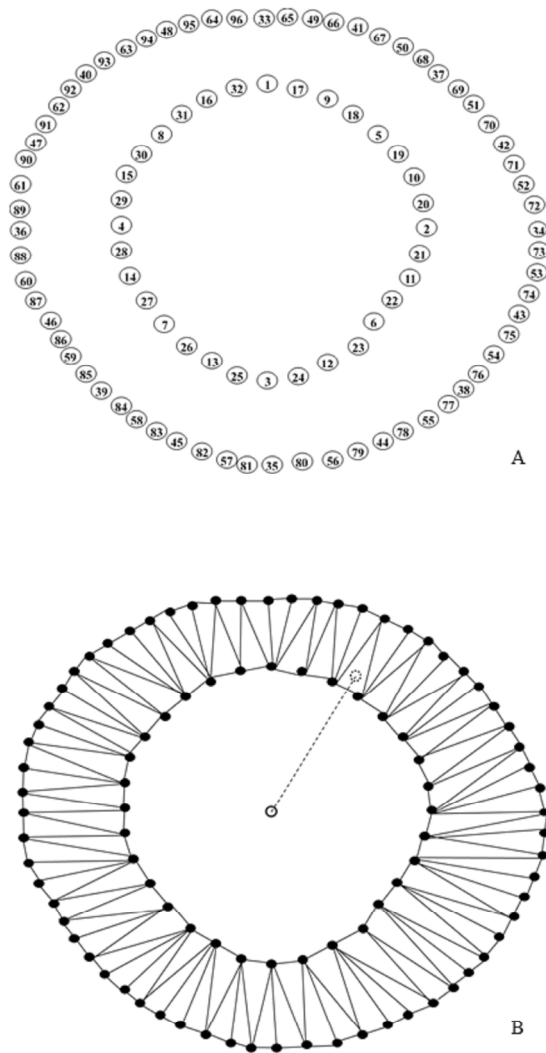


Figure 2. A) Schematic of digitised points. Numbers represent the order in the sequence in which the point was digitised. B) The 96 triangles used in the calculation of cross-sectional area and moment of inertia. For one example triangle, the distance from the slice centroid (circle) to the triangle centroid (dashed circle) is highlighted, as used in the calculation of the cross-sectional moment of inertia.

476x635mm (96 x 96 DPI)

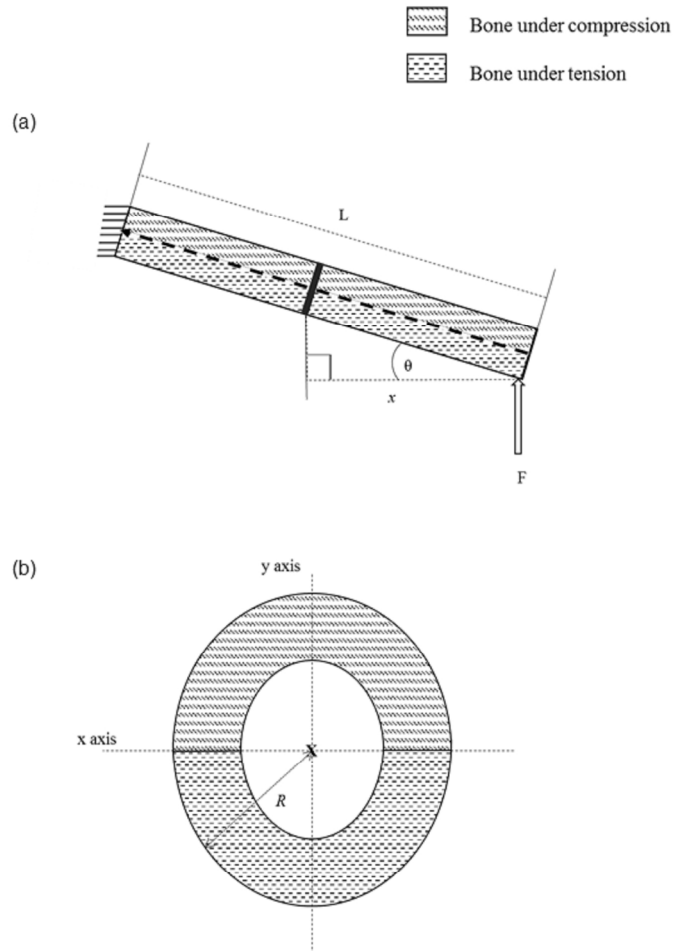


Figure 3. Schematic showing the inputs and measurements considered in the model. (a) Displays the free-body representation of the third metatarsal, in which the axially-directed dashed line () represents the line of axial stress; θ = angle of inclination of metatarsal to the ground; F = vertical force obtained from pressure data; L = length of metatarsal; x = perpendicular distance of slice from point of force application; the thick black intersection represents a sample slice taken from the mid-shaft. This slice is depicted from a frontal perspective in (b), where X = Centroid of slice; R = radius of outer surface of metatarsal. The axes about which bending stress moment arms (y) and inertial properties are calculated are also identified.

476x635mm (96 x 96 DPI)