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1 **Minimising Tibial Fracture after Unicompartamental Knee Replacement: A**
2 **Probabilistic Finite Element Study**

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24

25 **Abstract**

26 *Background*

27 Periprosthetic tibial fracture after unicompartmental knee replacement is a challenging
28 post-operative complication. Patients have an increased risk of mortality after fracture, the
29 majority undergo further surgery, and the revision operations are less successful.
30 Inappropriate surgical technique increases the risk of fracture, but it is unclear which
31 technical aspects of the surgery are most problematic and no research has been performed on
32 how surgical factors interact.

33 *Methods*

34 Firstly, this study quantified the typical variance in surgical cuts made during
35 unicompartmental knee replacement (determined from bones prepared by surgeons during an
36 instructional course). Secondly, these measured distributions were used to create a
37 probabilistic finite element model of the tibia after replacement. A thousand finite element
38 models were created using the Monte Carlo method, representing 1000 virtual operations, and
39 the risk of tibial fracture was assessed.

40 *Findings*

41 Multivariate linear regression of the results showed that excessive resection depth and
42 making the vertical cut too deep posteriorly increased the risk of fracture. These two
43 parameters also had high variability in the prepared synthetic bones. The regression equation
44 calculated the risk of fracture from three cut parameters (resection depth, vertical and
45 horizontal posterior cuts) and fit the model results with 90% correlation.

46 *Interpretation*

47 This study introduces the application of a probabilistic approach to predict the aetiology of
48 fracture after unicompartmental knee replacement and has quantified the potential importance
49 of surgical saw cut variations for the first time. Targeted changes to operative technique can
50 now be considered to seek to reduce the risk of periprosthetic fracture.

51 Keywords: Knee, Bone, Fracture, Unicompartmental, Finite Element.

52

53 **1 Introduction**

54 Periprosthetic tibial fracture after unicompartmental knee replacement (UKR) is a severe
55 complication which can be challenging to treat and manage [1]. Fracture is associated with
56 increased mortality and significant morbidity, and is increasing in incidence [2]. Of the cases
57 of tibial fracture after UKR reported in the literature [1; 3-11], approximately half of the
58 fractures occurred during the operation, and half occurred within 6 weeks post-operatively.
59 More than 50% of the reported case studies end with revision to total knee replacement,
60 requiring removal of the cruciate ligament(s) and leading to reduced knee function [1; 3-11].
61 The reported incidence of tibial fracture after UKR ranges from 0.8% [1] to 5.0 % [11]. The
62 absolute number of patients at risk of fracture is rising [2] as a result of increasing numbers of
63 UKRs being performed each year [12], greater life expectancy [13], higher cases of
64 osteoporosis [14], and increasing patient activity [15]. It is, therefore, important to identify
65 which aspects of UKR surgery put patients at the greatest risk of fracture, so that the
66 operative technique can be optimised to minimise the occurrence of this serious complication.
67 The issue of periprosthetic fracture has been reported in several different unicompartmental
68 knee designs, so it appears the issue is not design-specific [1; 3-4; 6; 8; 11], though one study
69 suggested cementless components are at greater risk [16]. There is uncertainty in the
70 literature regarding the most important surgical risk factors for tibial fracture after UKR. The
71 surgical errors that have been proposed to cause tibial plateau fracture include:

- 72 • excessive depth of surgical cuts made for the tray, tray keel, or pegs [1; 4; 9; 17; 18]
- 73 • too many holes in the cortex for alignment guides [6; 10]
- 74 • perforation of the tibial cortex [5]

- 75 • under-sizing of the tibial tray [1; 3]
- 76 • use of excessive force when impacting the plateau [1]
- 77 • excessive removal of bone [1].

78 However, of these studies, Clarius *et al.* were the only authors to base their conclusions on
79 experimental evidence and showed that extended vertical cuts reduced the force required to
80 cause tibial fracture by 30% [18].

81 Finite element analysis (FEA) is a useful tool for predicting bone fracture, and it has been
82 applied most commonly to fractures of the femoral neck. Schileo *et al.* proposed a Risk Of
83 Fracture (ROF) criterion (Equation 1) which has been validated for hip fracture cases [19].
84 The ROF is calculated from the maximum principal strain (ϵ) within the bone divided by
85 elastic limit strain values. The criterion distinguishes between tensile and compressive
86 loading states, and high ROF values in a localised region indicate a higher risk of fracture.

$$87 \text{ ROF} = \begin{cases} \epsilon/0.0073 & \text{if tensile} \\ \epsilon/0.0104 & \text{if compressive} \end{cases} \quad (1)$$

88 An advantage of using FEA to examine risk factors for bone fracture is that the uncertainty
89 resulting from confounding factors is removed, enabling the study to focus on the parameters
90 of interest. The aim of this study was apply Schileo's fracture criterion and utilise
91 probabilistic FEA methods to assess which surgical parameters increase the risk of
92 periprosthetic fracture after unicompartmental knee replacement.

93 **2 Methods**

94 The study first quantified the surgical variability in the preparation of tibia for UKR, then
95 used the Monte Carlo method to virtually implant 1000 UKRs, representing that variability.

96 The risk of fracture for the finite element models was found and multivariate linear regression
97 used to assess the influence of each surgical cut parameter.

98 *2.1 Quantification of variability in surgical cuts*

99 Twenty three right tibial Sawbones (custom anatomic design made for Zimmer-Biomet UK
100 Ltd. by Sawbones, Pacific Research Laboratories Inc., Vashon Island, Washington, USA)
101 were prepared for medial mobile UKR (Oxford Partial Knee, Biomet, Bridgend, UK) as part
102 of an instructional course. The attendees were a mixture of experienced and inexperienced
103 orthopaedic surgeons who each prepared a Sawbone tibia after receiving training in the
104 operative technique. Measurements were then taken of the positions and depths of the
105 surgical cuts (Figure 1). The parameters examined were:

- 106 • the resection depth (the superior-inferior distance from the tibial plateau on the lateral
107 side to the resected medial horizontal cut, where the distance was parallel to the
108 mechanical axis)
- 109 • the angle between the horizontal and vertical cuts
- 110 • the depth of the vertical cuts, both at the posterior and anterior cortex
- 111 • the depth of the horizontal cuts, both at the posterior and anterior cortex
- 112 • the depth of the pin hole (used to hold the cutting guide)

113 *2.2 Finite element model*

114 *2.2.1 Geometry*

115 The finite element model was based on a previously published UKR tibial model that was
116 validated against cadaveric tests [20]. The tibial geometry was segmented from a CT scan of
117 a cadaveric tibia obtained from a male donor aged 60 years with a body mass index of 22.5.

118 The geometry was segmented using Mimics software (version 14.1, Materialise, Leuven,
119 Belgium) and smoothed using the Scanto3D function in SolidWorks software (version 2012,
120 Simulia, Waltham, MA, USA). The tibia was aligned so that the tibial mechanical axis was
121 the Z-axis, anterior-posterior was the X-axis, and medial-lateral was the Y-axis. Previous
122 work verified that use of a shortened tibia improves computational speed without affecting
123 the strain in the periprosthetic region [21]. Therefore, the length of the tibia was shortened to
124 100 mm proximally.

125 The UKR was implanted virtually using Boolean functions within ABAQUS software
126 (Version 6.12, Dassault-Systèmes, Rhode Island, USA). A Python script (version 2.6, Python
127 Software Foundation) was created to automate the implantation for different surgical and
128 loading parameters. The width of all saw cuts used was 1 mm, which is the width of the saw
129 blade used during surgery [22]. The base of the Oxford Unicompartmental Knee tibial tray
130 was fully fixed to the tibia, and frictionless contact was defined between the tray wall and the
131 bone. Neither the effect of interference fit nor loosening was examined in this study.

132 *2.2.2 Mesh*

133 The finite element mesh was created using ABAQUS software. Quadratic tetrahedral
134 elements (C3D10) were used to mesh the bone and the tibial tray was meshed with
135 quadrilateral rigid elements (R3D4). A smaller element size (a third of the overall element
136 size) was assigned to; the muscle attachment sites, the edges created by the saw cuts, and the
137 drilled pin-hole.

138 A mesh convergence study was performed to determine the optimal mesh density, where
139 convergence was defined as when the output was within 5% of the next three finer element

140 sizes (0.1 mm mesh size intervals). The model converged for both output parameters at an
141 overall element size of 2.4 mm.

142 2.2.3 *Material properties*

143 The tray was modelled as a rigid cobalt chromium-molybdenum alloy with a density of
144 8.4 g cm^{-3} [23]. The tibia was modelled as a heterogeneous linear elastic material, where the
145 modulus of each element was assigned based on the corresponding gray scale value of that
146 element in the CT scan of the tibia. The bone material assignment was performed with
147 Mimics software (400 material intervals with a modulus range of 1 to 22 GPa, consistent with
148 previous work [20]).

149 2.2.4 *Musculoskeletal model*

150 The muscle and contact loads applied to the tibia throughout the gait cycle were estimated
151 using data from an instrumented total knee replacement (TKR) implanted in a male subject
152 (age: 83 years, BMI: 22.5, alignment: neutral) at the Shiley Center for Orthopaedic Research
153 and Education at the Scripps Clinic in California [24]. The data were recorded while the
154 patient performed overground walking trials at a self-selected speed [25; 26] and included the
155 following quantities: contact forces on the tibial tray, ground reaction forces and moments,
156 surface marker positions, and electromyographic (EMG) data. Medial and lateral tibial
157 contact forces were calculated from the implant load cell data using an elastic foundation
158 contact model [27]. Muscle force estimates were generated using static optimization of a
159 subject-specific knee model which minimized (the sum of the squares of) muscle activations.
160 The measured tibio-femoral contact forces and net (inverse-dynamic) knee loads were also
161 matched as part of this optimization, and muscle force estimates were generated using static
162 optimization of a subject-specific knee model with two cost functions (based on muscle

163 ~~activations and contact forces~~) [28] constructed in OpenSim [29]. The musculoskeletal knee
164 model and muscle force estimation approach have been described in detail in a previous study
165 [23].

166 2.2.5 *Boundary conditions*

167 The muscle and contact loads from the musculoskeletal model were applied to the FE model
168 using distributed coupling to the tibial attachment site (Figure 2). On the lateral side the
169 compartment loads were applied to the tibial articular surface in the same manner, while on
170 the medial side the compartment load was applied to the upper surface of the tibial tray using
171 an equation derived in a previous study to represent the pressure field [23]. The distal end of
172 the tibia was fixed in all degrees of freedom.

173 The cadaveric tibia used for the finite element model in the present study was different from
174 the instrumented knee subject tibia. Both tibias were from male subjects with a similar body
175 mass index (instrumented tibia: 22.5 and cadaveric tibia: 25.9) and size (instrumented tibia:
176 75.0 mm tibial width, and cadaveric tibia: 76.5 mm tibial width) but different age
177 (instrumented tibia: 83, cadaveric tibia: 60). An iterative closest point (ICP) algorithm was
178 used to register the two tibias and determine the muscle attachment sites and vectors for the
179 new geometry.

180 2.2.6 *Post-processing*

181 The risk of fracture parameter described by Schileo et al. [19] (Equation 1) is not
182 automatically calculated by ABAQUS software, so a custom Python script was written to
183 interact with ABAQUS and calculate the new field output. The two outputs used for the
184 analysis were: (1) the maximum ROF value (omitting artificially high results at muscle

185 attachment sites), and (2) the total volume of elements exceeding an ROF of 1 (threshold for
186 fracture defined by Schileo).

187 2.3 Application of the Monte Carlo method

188 The measurements taken from the tibia prepared during the surgical training course (Section
189 2.1, Figure 1) were used to define the envelope of surgical cut variation for the models. A
190 thousand finite element models were then created to represent the variance in surgical
191 technique.

192 The distribution of each surgical cut parameter was categorised from the measured data using
193 the Kernel Density function from the ‘scikit-learn’ machine learning module implemented in
194 Python [30]. A Gaussian kernel ($K(x; h)$) was applied with a bandwidth (h) of 0.75, to create
195 the function representing the distribution of cut parameters measured from the sawbones. The
196 kernel has the form given in Equation (2) where the density estimate at point y is found from
197 the provided group of points $x_i; i = 1 \dots N$.

$$198 \quad \rho_K(y) = \sum_{i=1}^N K\left(\frac{y - x_i}{h}\right) \quad (2)$$

199

200 An ABAQUS-python script was then used to automate the creation of each finite element
201 model. The script involved the following steps:

- 202 1. Randomly select each surgical cut parameter from its calculated distribution, using
203 Python ‘random’ and ‘scikit-learn’ packages.
- 204 2. Prepare tibia using Boolean operations
- 205 3. Assemble tibia and UKR components
- 206 4. Apply muscle loading, joint loading, constraints. and materials

207 5. Mesh and solve

208 To confirm that 1000 models were sufficient to achieve convergence of the Monte Carlo
209 method, we used the method described by Fishman *et al.* [31]. Convergence was defined
210 when the mean and coefficient of variance of both risk of fracture output parameters were
211 within 3% of their values from the last 10% of valid instantiations [31; 32].

212 2.4 Model verification

213 The finite element model was verified two ways: (1) the location of elements at risk of
214 fracture were compared to typical clinical fracture locations [1] and (2) the maximum ROF in
215 the periprosthetic region was compared with failure loads reported by Clarius *et al.* [18]. To
216 replicate the experiments performed by Clarius an increasing load (max 10 kN) was applied
217 to the medial compartment while the two risk of fracture criteria were recorded. The tibia was
218 analysed with, and without an extended vertical cut (cut angled at 10 degrees [18]). No
219 muscle or lateral compartment loading was applied.

220 2.5 Statistical analysis

221 Which parameters influenced the risk of fracture was determined by performing an analysis
222 of variance (ANOVA) test. The parameters which significantly ($p < 0.05$) influenced the risk
223 of fracture were then input into a generalised linear regression (GLM) model. All statistical
224 analyses were implemented in R (www.r-project.org). To ensure the dependent variables
225 (maximum ROF and Volume of failed elements) were normally distributed for the ANOVA
226 and GLM model, we transformed the data by taking the logarithm of the maximum ROF and
227 the cube root of the volume of failed elements.

228 **3 Results**

229 *3.1 Quantification of variability in surgical cuts*

230 The measurements of the prepared tibial Sawbones highlighted large variability in the vertical
231 and horizontal cuts posteriorly (Table 1). The standard deviation in the anterior cut depths
232 was half that of the posterior cuts. Furthermore, in 14 of the 23 Sawbone tibias, the pin hole
233 had gone into the keel slot, greatly increasing the hole depth and producing a bi-modal
234 distribution with a high standard deviation. The cut angle had very low variability (percent
235 deviation 1.6%) and so was not included in the Monte Carlo models.

236 *3.2 Application of the Monte Carlo method*

237 A linear relationship was found between medial contact force and the maximum ROF when
238 loaded through the whole gait cycle ($R^2 = 0.83$), despite the varying muscle loads and load
239 vectors from the musculoskeletal model (Figure 3). The maximum ROF value and the
240 maximum volume of failed elements occurred at 16% of the gait cycle, so these results were
241 used for the regression analysis.

242 The ANOVA results (Table 2) found the extension of the vertical cut posteriorly (e), the
243 resection depth (a), and extension of the horizontal cut posteriorly (f) to significantly
244 influence both the maximum ROF value and the volume of failed elements. Consequently,
245 these parameters were used to create the regression model. The correlation between both
246 output variables and the posterior vertical and horizontal cuts and the resection depth was
247 also confirmed visually (Figure 4).

248 The multivariate linear regression model found that the greater the resection depth and the
249 more extended the posterior vertical cut, the greater the risk of fracture in terms of both the

250 maximum ROF and the volume of failed elements. In contrast, extension of the horizontal cut
251 posteriorly reduced the risk of fracture slightly. The parameters which most influenced the
252 risk of fracture were the resection depth and extension of the vertical cut posteriorly, as can
253 be seen from the 3-dimensional scatterplot shown in Figure 5.

254 From the known resection depth, posterior vertical cut, and posterior horizontal cut for each
255 of the 1000 models, the regression equations were used to calculate the maximum ROF value
256 (Equation (3)) and the volume of failed elements (Equation (4)). The equations were able to
257 predict the finite element maximum ROF with a Pearson's correlation coefficient of 0.59 and
258 the volume of failed elements with a 90% correlation, indicating a reasonable regression
259 model fit.

$$260 \quad \text{Max ROF} = 10^{(0.0152e + 0.0161a - 0.0052f + 0.102)} \quad (3)$$

$$261 \quad \text{Volume of failed elements} = (0.0454e + 0.061a - 0.029f + 0.267)^3 \quad (4)$$

262 Where: (*a*) is the resection depth, (*e*) is the extension of the vertical cut posteriorly, and (*f*) is
263 the extension of the horizontal cut posteriorly.

264 3.3 Model Verification

265 When the tibia was prepared and loaded in the same manner as described by Clarius *et al.*
266 [18], regions of high ROF were observed in the corner between the horizontal and the vertical
267 cut and in the region surrounding the keel. At high loads, these two regions combined to
268 create a line of high fracture risk extending to the tibial cortex (Figure 6). The line matched
269 the path of fractures observed clinically [1], confirming that the ROF parameter is an
270 indicator of tibial fracture risk.

271 The average failure load reported by Clarius *et al.* for a tibia with an excessive vertical cut
272 was 2.6 kN (range 1.08-5.04), and 3.9 kN (range 2.35-8.50) for a the tibia with a perfect cut
273 [18]. The finite element models when loaded under these conditions had corresponding
274 maximum ROF values of 5.2 and 5.6, and volume of failed elements of 128 mm³ and 177
275 mm³, respectively. These results indicate that a maximum ROF value above 5, with a failure
276 volume greater than 128 mm³, would represent a high fracture risk. From the 1000 models
277 examined in the Monte Carlo simulation, 0.3% had a maximum ROF greater than 5; none
278 reached the volume threshold.

279 **4 Discussion**

280 This study used a probabilistic finite element modelling approach to investigate the influence
281 of different surgical cuts used to prepare the tibia for unicompartmental knee replacement on
282 the risk of periprosthetic fracture. Of the surgical parameters investigated, excessive resection
283 depth and an extended posterior vertical saw cut were found to significantly increase the risk
284 of fracture according to the regression model. Furthermore, based on measurements of the
285 Sawbone tibias prepared by surgeons as part of an instructional course, the depths of the
286 vertical saw cuts posteriorly are highly variable. This combination of results is concerning,
287 as high variability in a factor believed to increase the risk of fracture increases uncertainty in
288 the surgical outcome.

289 The tibial saw guide is an important part of the surgical instrumentation for making the
290 vertical saw cut. The guide comprises a rectangular block, which is pinned to the anterior
291 side of the tibia (causing the pin holes described) and provides a horizontal surface to stop the
292 saw blade when making the vertical cut. Although the guide provides a stop anteriorly, there
293 is no such stop posteriorly, and the surgeon is required to estimate the correct cut angle (7

294 degrees). The guide is also used to aid the horizontal cut, where the flat side of the
295 reciprocating saw rests on the top of the block which ensures the cut is straight and has a 7
296 degree posterior slope [22]. If the surgeon under-estimates the slope of the vertical cut, the
297 horizontal and vertical cuts will not meet and the vertical cut will need to be extended to
298 enable the worn tibial plateau to be removed. If the surgeon over-estimates the slope, the
299 vertical cut will be excessive, causing a posterior notch. It is, therefore, difficult for a
300 surgeon to ensure that the vertical cut is not excessive with the current operative technique,
301 and limited posterior visibility makes it hard to identify cut depth intra-operatively.

302 The resection depth is controlled by the height at which the tibial guide is pinned. The
303 operative technique suggests the level should be 2 to 3 mm lower than the eroded bone [22].
304 Several studies have suggested that errors in the vertical cut increase the risk of fracture [1; 9;
305 17], and Clarius *et al.* demonstrated this relationship experimentally [18]. However,
306 resection depth has been proposed by only one other publication as a critical parameter and is
307 largely overlooked in the literature [1]. If clinicians were made aware that excessive
308 resection can contribute to fracture, it would be simple for them to modify their surgical
309 practice accordingly.

310 Regardless of the manufacturer or implant type, all UKR designs require an L-shaped space
311 to be created for the tibial component, which requires a horizontal resection cut and a vertical
312 cut to be made by the surgeon. This consistency in UKR surgical technique may explain why
313 tibial plateau fracture is not restricted to only one device design [3; 5; 6; 8]. By knowing the
314 surgical factors which may increase tibial fracture risk, surgeons and orthopaedic
315 manufacturers can begin to propose solutions that can minimise the risk of fracture after
316 UKR.

317 Interestingly, the finite element model which simulated loading throughout a whole gait cycle
318 found a linear relationship between the risk of fracture and the medial load. Rudol *et al.*
319 suggested that peri-prosthetic fracture after UKR may be linked to patient weight [9], and our
320 results indicate it could be a risk factor. Whether high body mass index should be considered
321 a contraindication for UKR is a controversial topic, with evidence both for [33] and against
322 [34; 35]. Some case studies in the literature have mentioned limiting weight-bearing and
323 using medial unloading braces to offset the medial load in cases of peri-prosthetic fracture to
324 aid healing [3; 10], but not as a preventative measure. In patients considered at risk, bracing
325 could be used as a non-invasive treatment.

326 Periprosthetic tibial fractures after UKR can occur intraoperatively or post-operatively [1; 9].
327 Reports of intraoperative fracture describe a high strain-rate impact load which causes the
328 bone to fracture [3; 5]. Post-operative fractures are associated with a combination of intra-
329 operative damage and cumulative damage from cyclic loading of the bone [36]. Studies of
330 patient activities after knee replacement have shown that in a typical day a patient will stand
331 for 21% of the time, walk for 8%, and climb stairs for 1%; the remaining time is non-weight
332 bearing [37]. In terms of cyclic loading, gait is therefore the most likely activity to cause
333 post-operative peri-prosthetic fracture, though the largest medial contact forces occur for stair
334 ascent and descent [38]. Our finite model did not examine the development of cumulative
335 strains within the bone, but both static [19] and fatigue mechanisms of bone fracture [36]
336 have been related to strain.

337 It is important to consider the limitations of this work. The model has been created to
338 represent the strains after UKR for one tibia to a high degree of accuracy, but no conclusions
339 can be made regarding variation within the population (e.g. in gait, bone shape, or bone

340 density). The load data which were applied to the model were based on results from an
341 instrumented total knee replacement, rather than from a unicompartmental knee replacement.
342 As UKR forces have never been measured directly *in vivo*, it is not possible to know whether
343 the load distribution between the condyles is equivalent. However, an anatomic approach
344 was used to implant the instrumented TKR [38], and therefore alignment should have been
345 similar to an implanted UKR with a similar load distribution between the condyles. This
346 study also makes the assumption that the cuts made during an instructional course are
347 representative of a surgical scenario, but there will be differences. For example, the Sawbone
348 tibias will feel different to real bone so feedback from the saw will be different, and the saw
349 itself may be a different model to that used in theatre. Since this study was performed new
350 Microplasty instrumentation has also been introduced by the manufacturers which assist the
351 surgeon with selecting an appropriate horizontal cut height, so should reduce the risk of
352 fracture. Furthermore, at the instructional course the surgeons will be new to the technique
353 and more likely to make errors and have increased variability. Therefore the results of this
354 study can be considered to represent a worst-case scenario. ~~In addition~~ Finally, our model
355 assumed perfect fixation of the base of the tibial tray to the bone and so could not consider
356 component loosening or interference fit. Incorporating loosening and interference fit adds
357 significant complexity to the model and is planned for inclusion in future work.

358 In conclusion, the results of this study have highlighted the importance of careful surgical
359 preparation of the tibial plateau prior to UKR implantation. This study suggests that the cause
360 of fracture is multifactorial and that to minimise the risk of fracture, a surgeon should;

- 361 • ensure that the vertical cut does not go too deep posteriorly
- 362 • be conservative with resection of the tibia

363 It may be possible to reduce the likelihood of an excessively deep vertical cut by altering the
364 surgical technique. If the horizontal cut were made before the vertical cut, a shim could be
365 inserted into the horizontal saw cut to stop the vertical cut from going too deep. Surgeon
366 training and better communication of the fracture risks could encourage surgeons to be more
367 conservative when resecting the tibia. If orthopaedic manufacturers and surgeons worked to
368 implement these changes in operative technique, our results suggest that the risk of tibial
369 plateau fracture after UKR could be reduced.

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484 **Tables**

Parameter	Mean	Standard Deviation	0%	25%	50%	75%	100%
a (resection depth, mm)	8.8	1.7	5.0	8.0	9.0	10.0	11.0
b (angle between cuts, deg)	90.6	1.4	88.0	90.0	90.0	91.0	95.0
c (vertical cut anterior, mm)	0.5	1.0	0.0	0.0	0.0	0.3	4.0
d (horizontal cut anterior, mm)	0.7	0.9	0.0	0.0	0.0	1.0	3.0
e (vertical cut posterior, mm)	4.2	3.9	0.0	0.0	4.0	7.0	12.0
f (horizontal cut posterior, mm)	1.3	2.1	0.0	0.0	1.0	1.3	7.5
g (pin depth, mm)	28.6	6.8	8.0	25.0	30.0	33.5	36.0

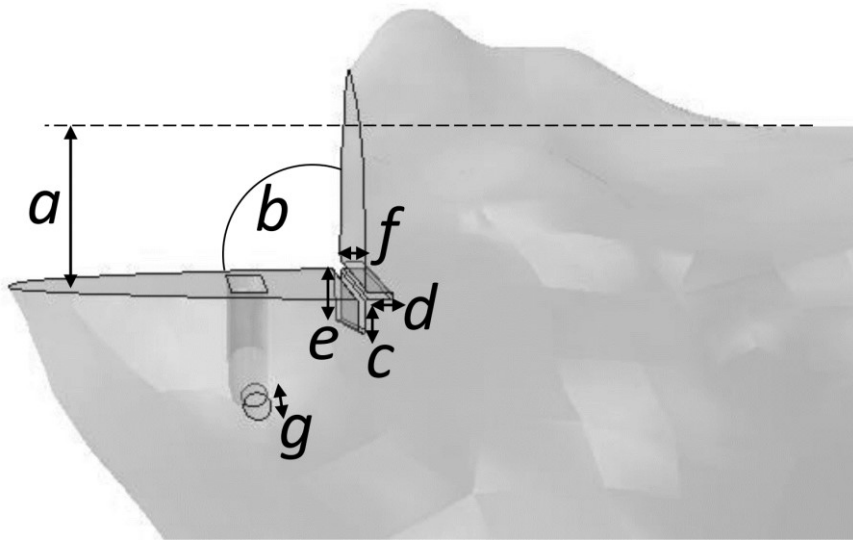
485 Table 1. The surgical cut parameters measured from 23 synthetic tibias prepared by surgeons
 486 during an instructional course. The mean value, standard deviation and distribution
 487 percentiles for each parameter are summarised.

Parameter	Maximum ROF value			Volume of failed elements		
	F	p	Sig	F	p	Sig
a (resection depth, mm)	183.4	2.2e-16	***	1295.5	2.2e-16	***
c (vertical cut anterior, mm)	0.1	0.028	*	0.04	0.843	NS
d (horizontal cut anterior, mm)	21.2	0.709	NS	21.3	4.3e-06	***
e (vertical cut posterior, mm)	4.9	2.2e-16	***	2859.7	2.2e-16	***
f (horizontal cut posterior, mm)	628.8	4.8e-06	***	315.4	2.2e-16	***
g (pin depth, mm)	0.8	0.365	NS	0.3	0.565	NS

488 Table 23. ANOVA test of the null hypotheses that the surgical cut parameters do not
489 influence the maximum ROF value, and the volume of failed elements. The ANOVA F-value
490 (F), p-value (p) and significance (Sig) results (*=p<0.05, **=p<0.01, ***=p<0.001,
491 NS=p>0.5) are shown.

492

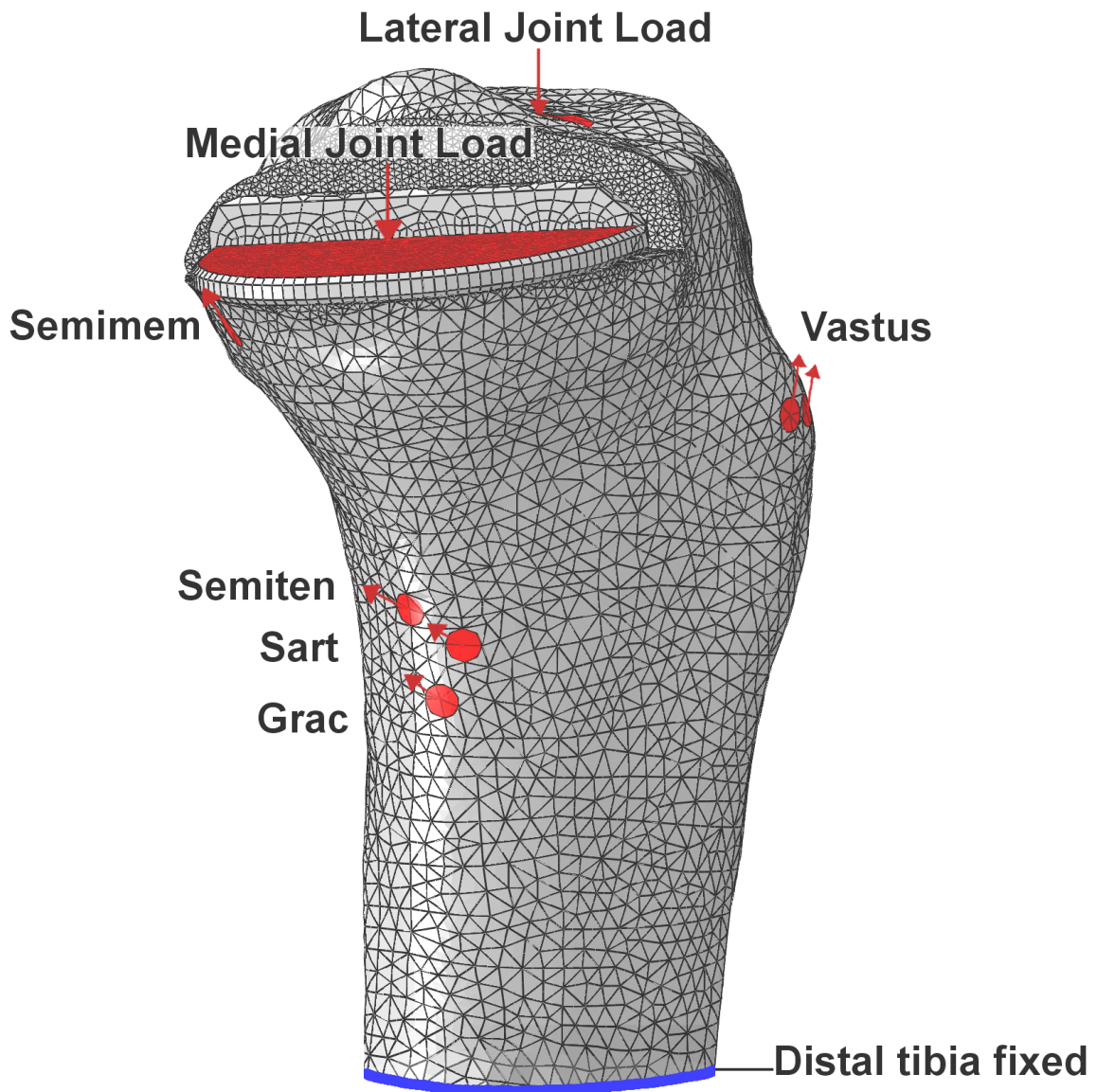
493 **Figure Legends**



494

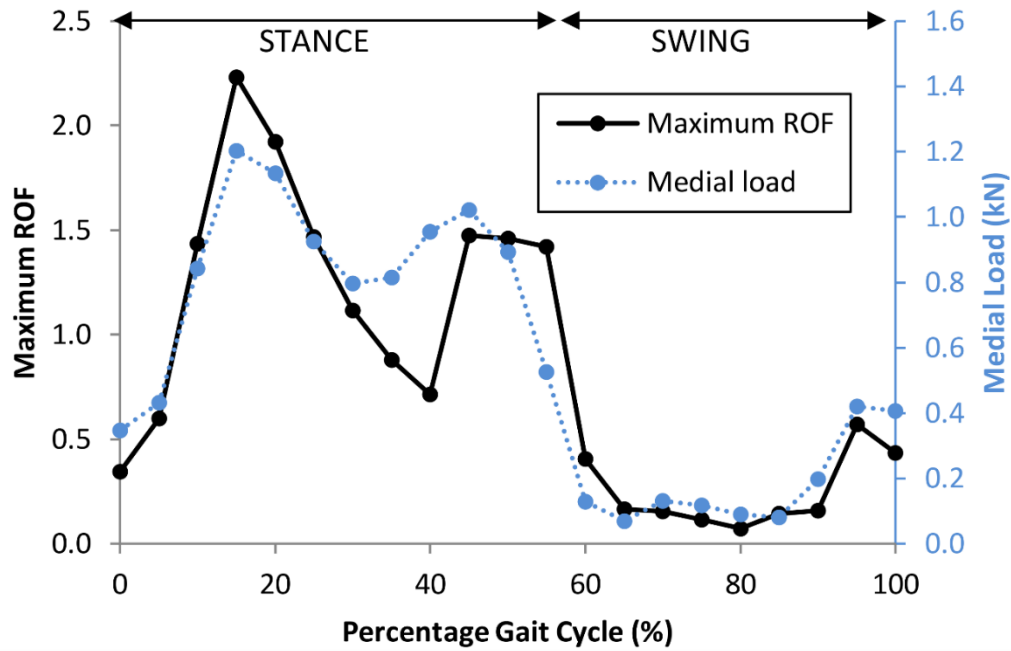
495 Figure 1. The surgical cut parameters measured from synthetic sawbone tibia were: the
496 resection depth (*a*), the angle between the horizontal and vertical cuts (*b*), the extension of the
497 vertical and horizontal cuts posteriorly (*e, f*) and anteriorly (*c, d*), and the depth of the pin
498 hole required to hold the cutting guide (*g*).

499

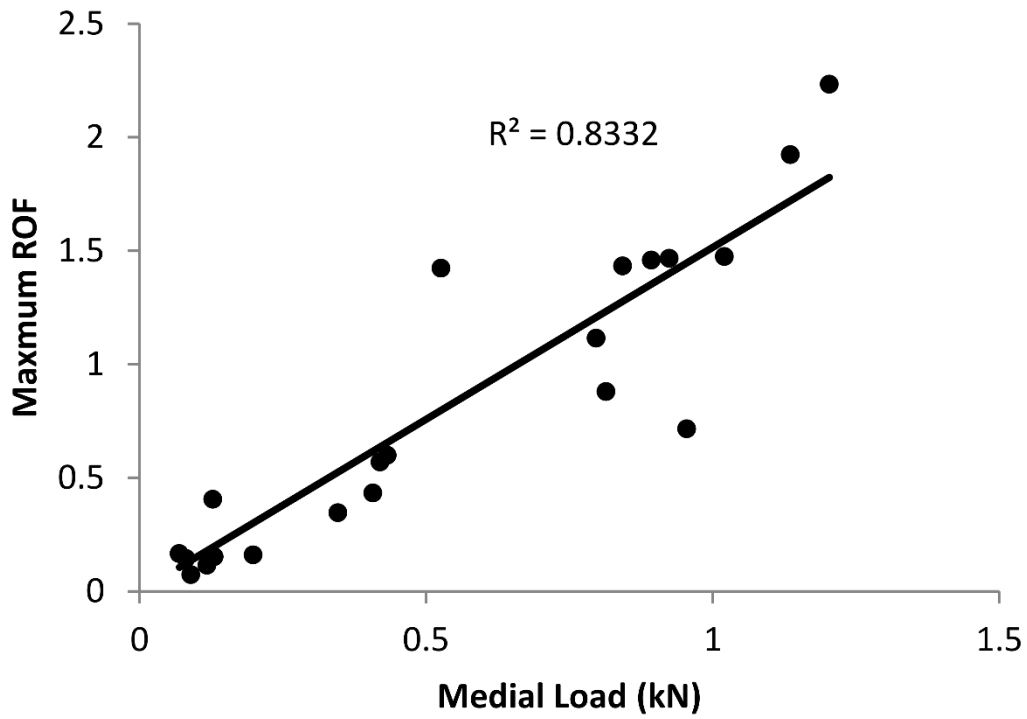


500

501 Figure 2. The constraint (blue), load locations, and vectors (red) applied to the model at 16%
 502 of the gait cycle. The medial view shown includes the gracilis (Grac), sartorius (Sart),
 503 semiteninosus (Semiten), semimembranosus (Semimem), vastus medialis, vastus intermedius
 504 and vastus lateralis (Vastus) muscles forces; the tensor fasciae latae muscle forces were also
 505 applied on the lateral side.



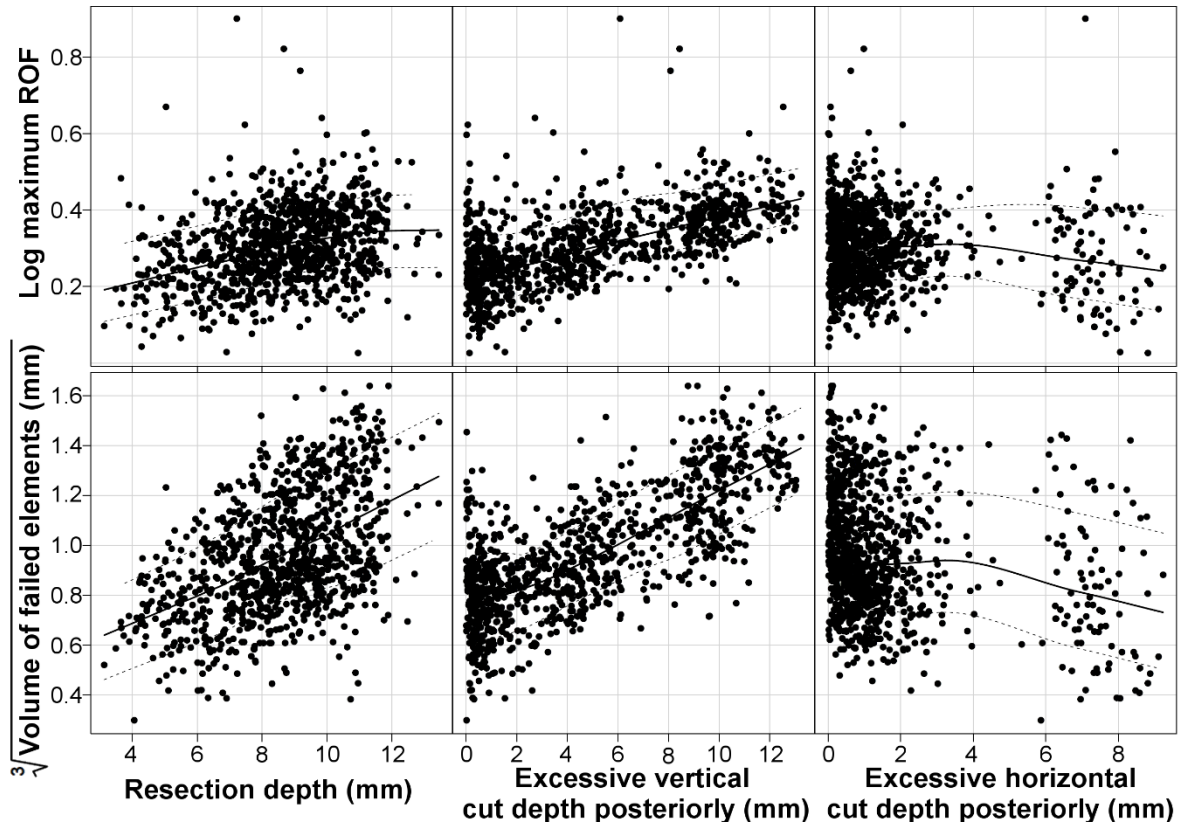
506 (a)



507 (b)

508 Figure 3. The risk of fracture (ROF) varied through the gait cycle (a) and a linear correlation
 509 was observed with medial load (b).

510



511

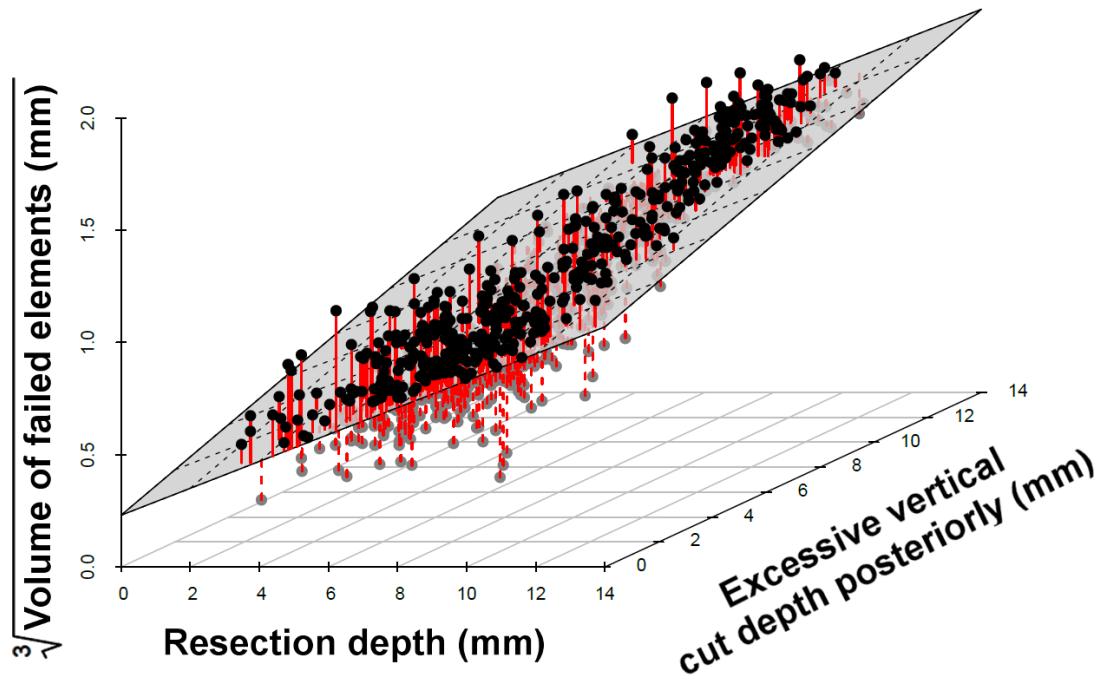
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Figure 4. Scatterplots of regression parameters which were found to significantly influence the maxim ROF value (log) and volume of failed elements (cube root). The lines in each plot represent the mean and the interquartile range.

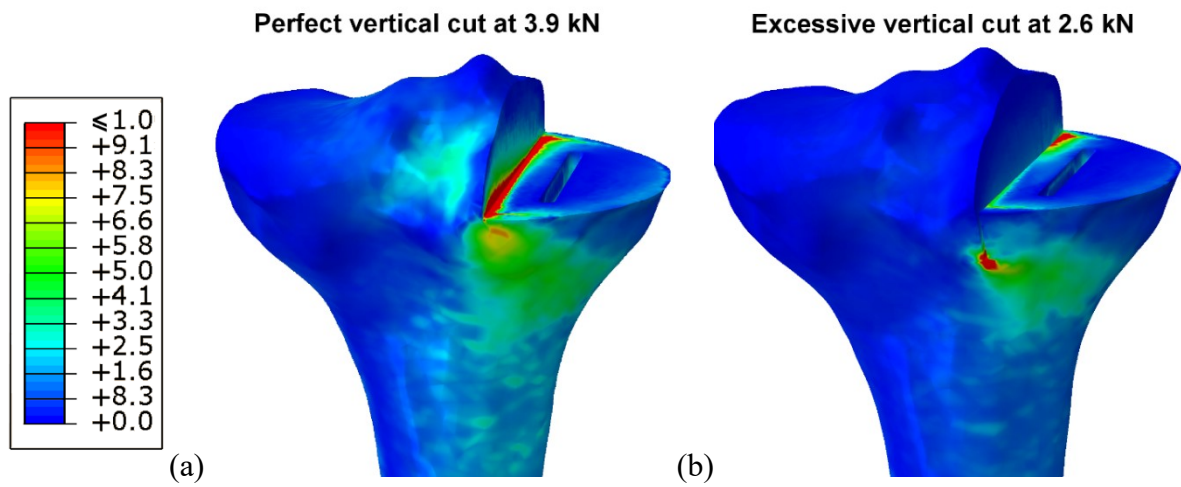


516

517 Figure 5. Scatterplot illustrating the dependence of the volume of failed elements on the
518 resection depth and the vertical cut. The multivariate regression model fit is represented by
519 the plane and the red lines indicate the residuals.

520

521



522

(a)

(b)

523 Figure 6. Distribution of the risk of fracture through a perfectly cut tibia loaded at 3.9 kN (a),
 524 and a tibia with excessive vertical cut loaded at 2.6 kN (b). Both models represent conditions
 525 which caused tibial fracture in experiments performed by Clarius *et al.*. The region most at
 526 risk of fracture extends diagonally from the vertical cut to the tibial cortex, via the keel.