

# **Optimal location for fibular osteotomy to provide maximal compression to the tibia in management of delayed and hypertrophic tibial non-union**

Anthony Lim<sup>\*a</sup>, Garance Biosse-Duplan<sup>\*a</sup>, Alastair Gregory<sup>b</sup>, Krishnaa T Mahbubani<sup>c</sup>, Fergus Riche<sup>b</sup>, Cecilia Brassett<sup>a</sup> and John Scott<sup>a</sup>

<sup>a</sup>Human Anatomy Teaching Group, Department of Physiology, Development and Neuroscience, University of Cambridge, CB2 3EL, UK; <sup>b</sup>Department of Engineering, University of Cambridge, CB2 1PZ, Cambridge; <sup>c</sup>Department of Surgery, Addenbrooke's Hospital, CB2 0QQ, Cambridge

\*AL and GBD contributed equally to this manuscript.

## **Corresponding author:**

Anthony Lim

Address for correspondence: Gonville & Caius College, Trinity Street, Cambridge UK

E-mail: [ajcl3@cam.ac.uk](mailto:ajcl3@cam.ac.uk)

## **Acknowledgements:**

The authors would like to thank the Department of Engineering for their invaluable help in building the rig and the technical staff in the Human Anatomy Centre for their assistance with the specimens. Most importantly, we would like to thank the donors and their families for their generosity without which this study would not be possible.

## **Highlights**

- Fibular osteotomies increase load in tibial fractures and are used to promote/enhance healing in cases of delayed or non-union
- A novel protocol using a rig was designed to ascertain the ideal location for a fibular osteotomy, and explained by a beam model
- An osteotomy proximal to the fracture site produces most tibial fracture loading

## **Abstract:**

**Background:** Tibial shaft fractures are the commonest long bone fracture, with early weight-bearing improving the rate of bony union. However, an intact fibula can act as a strut that splints the tibial segments and holds them apart. A fibular osteotomy, in which a 2.5cm length of fibula is removed, has been used to treat delayed and hypertrophic non-union by increasing axial tibial loading. However, there is no consensus on the optimal site for the partial fibulectomy.

**Methods:** Nine leg specimens were obtained from formalin-embalmed cadavers. Transverse mid-shaft tibial fractures were created using an oscillating saw. A rig was designed to compress the legs

with an adjustable axial load and measure the force within the fracture site in order to ascertain load transmission through the tibia over a range of weights. After 2.5cm-long fibulectomies were performed at one of three levels on each specimen, load transmission through the tibia was reassessed. A beam structure model of the intact leg was designed to explain the findings.

Results: With an intact fibula, mean tibial loading at 34kg was  $15.52 \pm 3.26$ kg, increasing to  $17.42 \pm 4.13$ kg after fibular osteotomy. This increase was only significant where the osteotomy was performed proximal to or at the level of the tibial fracture. Modelling midshaft tibial loading using the Euler-Bernoulli beam theory showed that 80.5% of the original force was transmitted through the tibia with an intact fibula, rising to 81.1% after a distal fibulectomy, and 100% with a proximal fibulectomy.

Conclusion: This study describes a novel method of measuring axial tibial forces. We demonstrated that a fibular osteotomy increases axial tibial loading regardless of location, with the greatest increase after proximal fibular osteotomy. A contributing factor for this can be explained by a simple beam model. We therefore recommend a proximal fibular osteotomy when it is performed in the treatment of delayed and non-union of tibial midshaft fractures.

**Key words:**

- Tibial fracture
- Delayed union
- Non-union
- Fibular osteotomy
- Fibulectomy
- Beam model
- Orthopaedic surgery
- Cadaveric study
- Weight bearing

## Introduction

Tibial shaft fractures are the commonest long bone fracture [1], with an estimated annual incidence of up to 21.5 per 100,000 population [2,3]. Sarmiento [4] and Brown & Urban [5] described the effective management of mild to severe tibial fractures by cast immobilisation with early weight-bearing. Although intramedullary nailing is currently the standard treatment for tibial fractures, the use of early weight-bearing in conjunction remains relevant and has been shown to improve the rate of bony union and thus be beneficial for healing [6]. However, an intact fibula can act as a strut that splints the tibial segments and holds them apart, thus limiting the beneficial effects of weight-bearing [7]. This may be a contributing factor to delayed and non-union in the tibia after intramedullary nailing, with tibial fractures having the highest risk of non-union among long bone fractures, with an incidence of up to 7.5% [8].

A fibular osteotomy, in which a 2.5cm length of fibula is removed, has been used to treat delayed and hypertrophic non-union by increasing axial tibial loading [9,10]. However, there is no consensus on the optimal site for the partial fibulectomy, with a lack of data on the effect of osteotomies performed at different levels on tibial loading. This study aimed to investigate the optimal location for a fibular osteotomy in cadaveric leg specimens by using a bespoke rig and protocol to measure tibial loading before and after fibulectomy at three different levels. In addition, the findings are explained using a simple beam model of the leg.

## Materials and Methods

### *Cadaveric tibial loading with an intact fibula*

Nine leg specimens were obtained from formalin-embalmed cadavers in the Human Anatomy Centre, Department of Physiology, Development and Neuroscience, University of Cambridge. The donors had provided written consent before decease for their bodies to be used in anatomical research in compliance with the Human Tissue Act 2004. There were 6 males and 3 females, with a mean age of 80.8 years (range 67-93). All specimens included the segment of the lower limb, with the soft tissue, from the tibial plateau to the talus. Transverse mid-shaft tibial fractures were created using an oscillating saw.

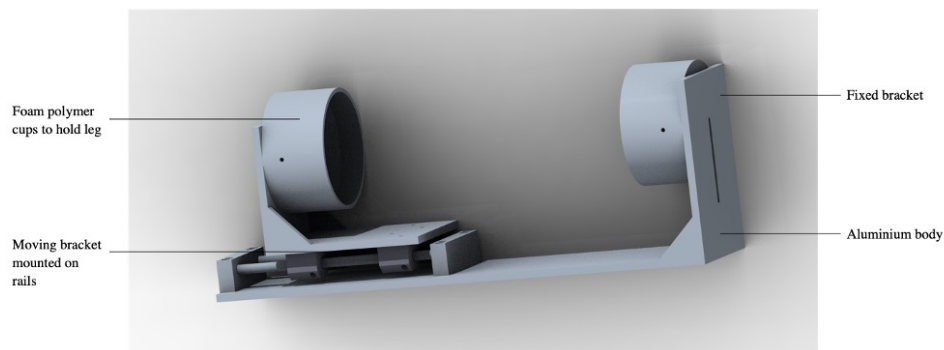


Figure 1 The rig used to carry out our experiment. Leg specimens were placed between the brackets and weights installed on a pulley system (not shown) pulled on the moving bracket, compressing the specimen.

A rig (Figure 1) was designed to compress the legs with an adjustable axial load and measure the force within the fracture site in order to ascertain load transmission through the tibia over a range of weights. Force within the fracture was measured using the Tekscan™ Flexiforce ELF system (Figure 2), which combined a force transducer and software to provide readings in N and kg.

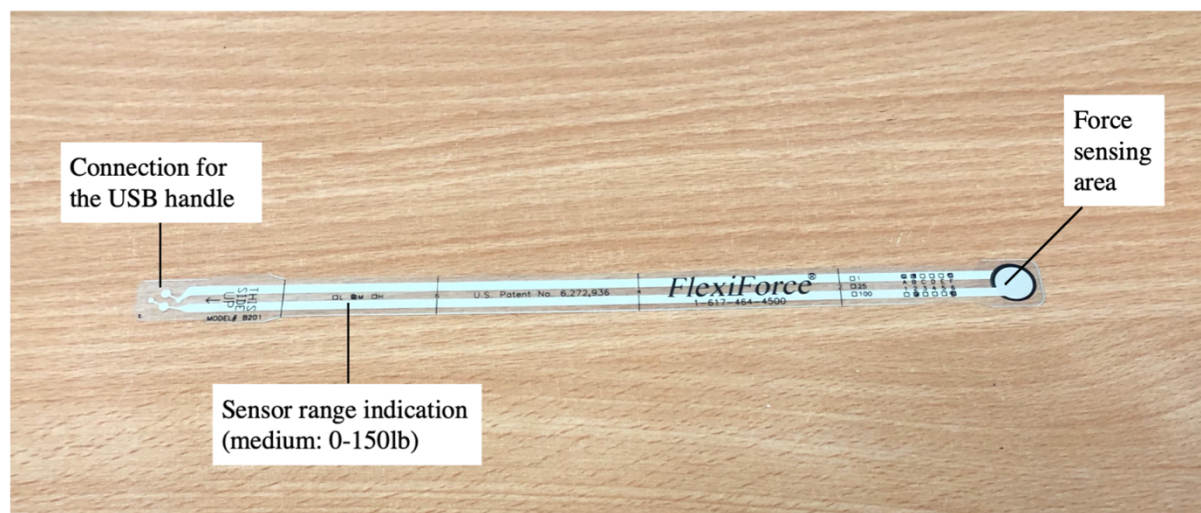


Figure 2 The force sensor used. A medium range sensor was chosen to maintain an appropriate sensitivity whilst avoiding the risk of saturating the sensor.

Specimens were placed in the rig and loaded with weights in 2.5kg increments across a range of 21.5-46.5kg (Figure 3). Six repeats were performed for each specimen. Graphs of mass sensed in the tibia across the range of added weights were drawn, and tibial loading at 34kg was then interpolated from the resulting linear trendline. 34kg was chosen as the weight for comparison

of tibial loading at three fibulectomy sites, as it represents half the mean mass of a human being [11], and is therefore most physiologically relevant.

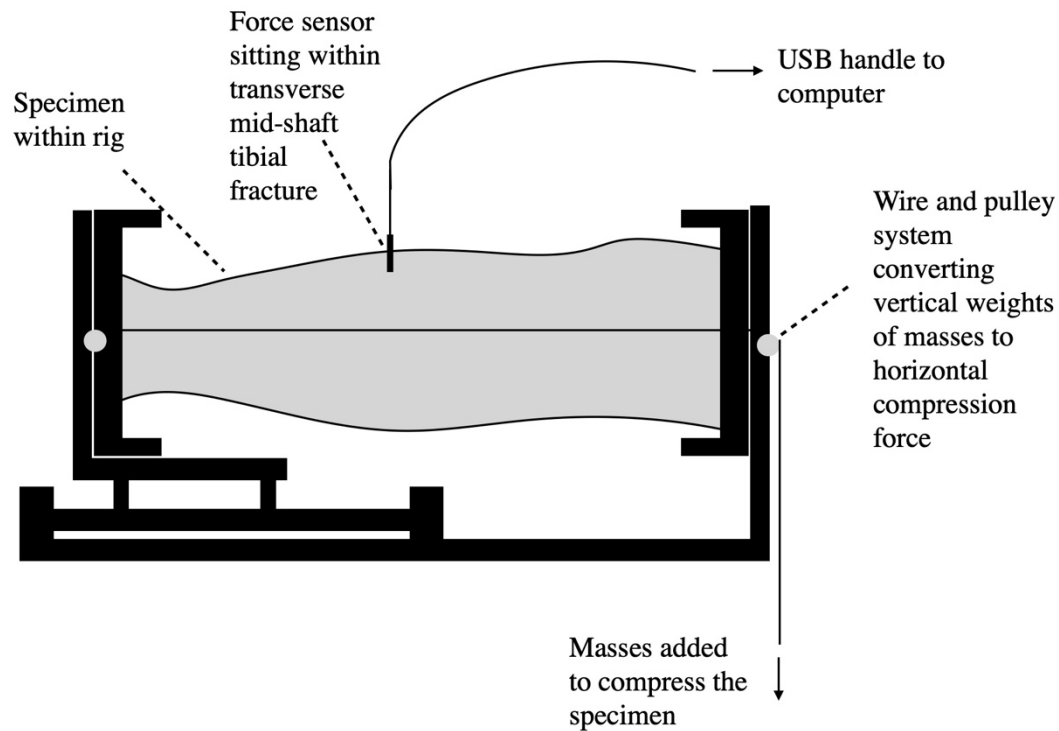


Figure 3 An illustration of the experimental set up, showing the specimen within the rig, with weights added converted to a compressive force through a wire and pulley system, and the force sensor inserted into the specimen to record tibial loading.

#### *Modelling tibial loading with a beam structure model*

A beam structure model of the intact leg was designed using graphic design tools on Microsoft Excel, comprising an L-shaped beam (tibia and tibial plateau) and a vertical beam (fibula, Figure 4). The superior tibiofibular joint was represented by a frictionless pin joint, allowing force transmission but without bending moments. Both beams were supported distally by the same support (talus), which prevented rotation as well as horizontal and vertical movements. This structure represented the basic bone structure of the leg, with lengths, areas and material properties obtained from literature (Table 1 [12–16]). Weight-bearing was simulated by a uniformly

distributed load on the tibial plateau.

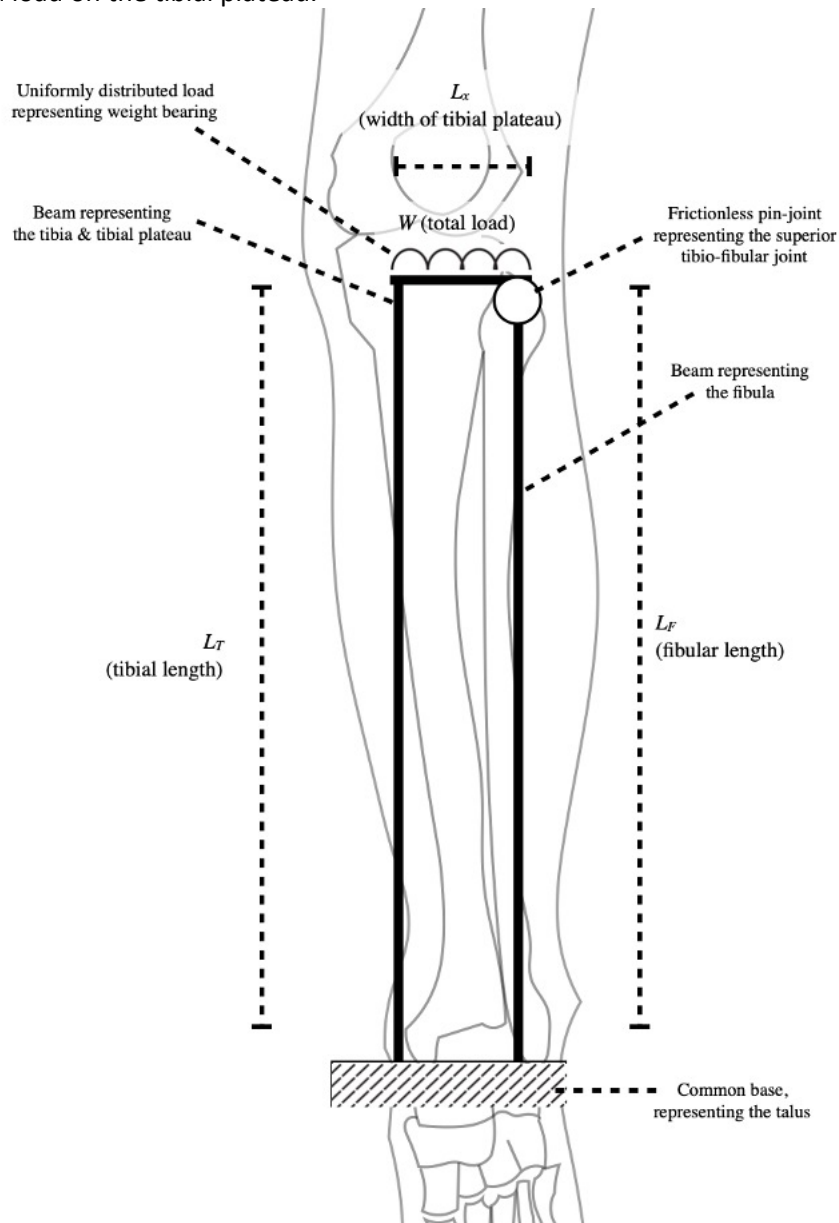


Figure 4 A beam structure model of an intact leg.

#### *Performing fibulectomies*

The 2.5cm-long fibulectomies were performed at one of three levels on each leg specimen: (1) distally, at 5cm proximal to the superior aspect of the lateral malleolus, (2) proximally, at 5cm distal to the lowest aspect of the fibular head, and (3) at the level of the tibial fracture (Figure 5). Load transmission through the tibia was then assessed on these specimens using the methodology described above.

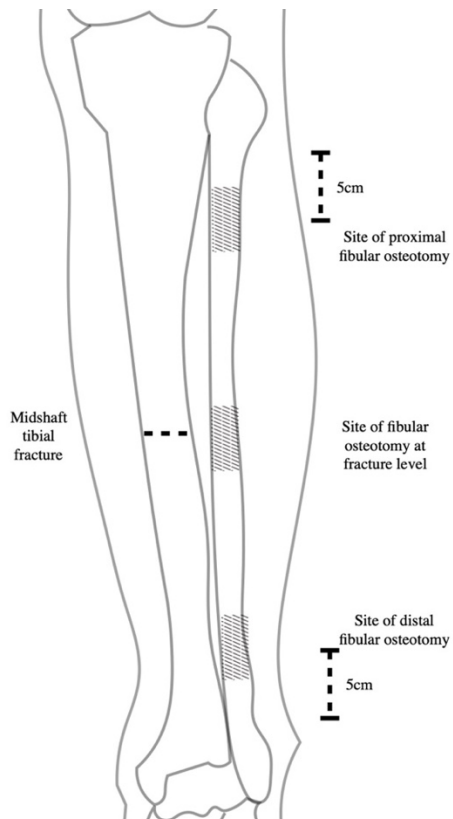


Figure 5 A diagram to show the location of the artificial fracture and osteotomies.

The beam structure model was adapted for post-osteotomy specimens by inclusion of the interosseous membrane, represented by an inextensible cord extending from the tibia down towards the fibula, able to transmit forces only when in tension. This orientation and material property reflect the *in vivo* interosseous membrane. Two beam structure models for distal and proximal fibulectomies are shown in Figures 6A and 6B respectively.

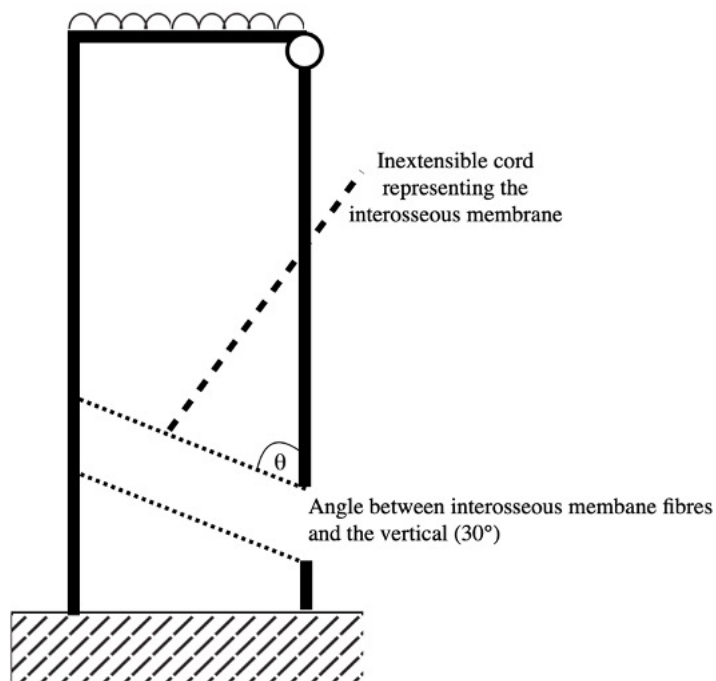


Figure 6A

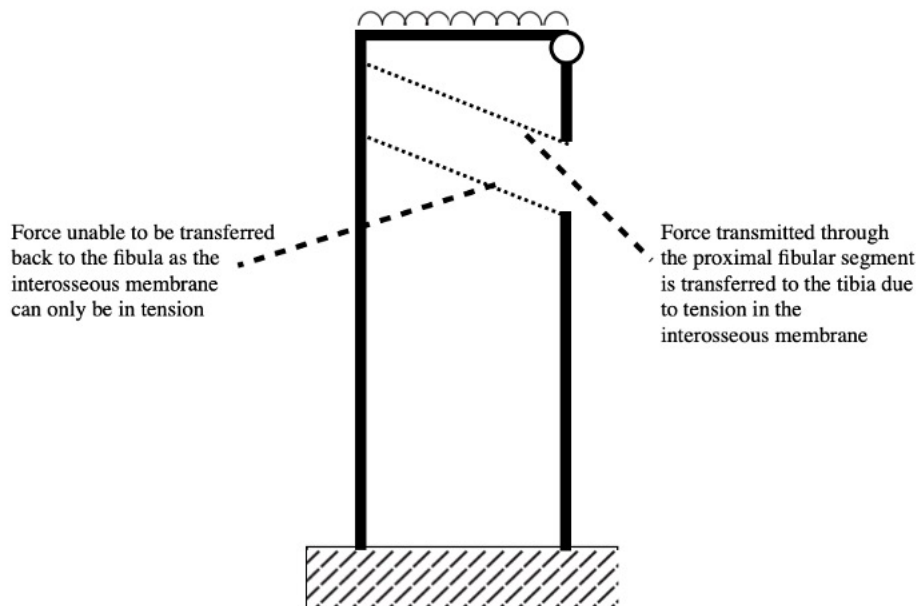


Figure 6B

Figure 6 A beam structure model of a leg after a fibular osteotomy performed (A) distally and (B) proximally.

#### Statistical analysis

Statistical analysis was performed using Graphpad Prism 8. Paired t-tests were used to compare tibial loading at 34kg before and after a fibular osteotomy for the six specimens as a group, with unpaired t-tests to compare pre- and post-osteotomy tibial loading for each leg. One-way



analysis of variance (ANOVA) was performed to compare percentage change in tibial loading between fibular osteotomies performed at the three different levels, with Tukey multiple comparison test used to compare: (1) proximally vs. *distally*, (2) proximally vs. at fracture level, and (3) at fracture level vs. distally. Data are presented as mean  $\pm$  SD unless otherwise stated. A P-value of  $<0.05$  was considered statistically significant.

## Results

### *Cadaveric and modelled tibial loading with an intact fibula*

The mean tibial loading at 34kg for all six specimens was  $15.52 \pm 3.26$ kg with an intact fibula.

With the beam structure model, due to the static indeterminacy of the model, midshaft tibial loading could not be calculated through principles of equilibrium alone and required the data on bone material properties obtained from literature (Table 1).

**Table 1**

List of constants and variables used in the beam model.

Name	Symbol	Value	Unit	Reference
Loading force	W	333	N	(a)
Tibial plateau length	$L_x$	0.0749	m	[12]
Tibial plateau bending stiffness	B	$10^{10}$	Nm <sup>2</sup>	(b)
Tibial axial length	$L_T$	0.35052	M	[13]
Tibial cross-sectional area	$A_T$	$2.933 \times 10^{-4}$	m <sup>2</sup>	[14]
Tibial Young's Modulus	$E_T$	$1.5886773 \times 10^{10}$	Pa	[15]
Fibular axial length	$L_F$	0.35306	m	[13]
Fibular cross-sectional area	$A_F$	$7.684 \times 10^{-5}$	m <sup>2</sup>	[14]
Fibular Young's Modulus	$E_F$	$1.4906108 \times 10^{10}$	Pa	[15]
Midshaft Tibial loading	F	To be calculated	N	

(a): For a value of mass added of 34 kg

(b): B is assumed to be large for the tibial plateau, of the order of  $E_T$  [16]

Applying Euler-Bernoulli beam theory [17] and considering the equilibrium in the system, the relationship between the applied load (W) and midshaft tibial loading was derived by hand (Equation 1). Microsoft Excel was then used to calculate midshaft tibial loading with a load of 334N applied using this equation, calculating midshaft tibial loading with an intact fibula to be 269N, *i.e.* 80.5% of the original force.

$$F = \frac{W \left( \frac{L_x^3 E_F A_F}{8 L_F B} + \frac{L_T E_F A_F}{L_F E_T A_T} \right)}{\frac{L_x^3 E_F A_F}{3 L_F B} + 1 + \frac{L_T E_F A_F}{L_F E_T A_T}} - W$$

Equation 1 The derived relationship between applied load (W) and midshaft tibial loading (F). Other variables and constants are listed in Table 1.

#### *After a distal osteotomy*

After a fibular osteotomy at any position, the mean tibial loading at 34kg for all six specimens was  $17.42 \pm 4.13\text{kg}$ , a statistically significant increase from the specimens with intact fibulas ( $P = 0.00439$ ). However, in specimens with a distal osteotomy, whilst an increase in tibial loading was demonstrated, this was not significant (Table 2,  $P=0.20336$  and  $P=0.36328$ ).

**Table 2**

Midshaft tibial loading with 34kg applied before and after a fibular osteotomy in each of the six specimens

<b>Fibular osteotomy location</b>	<b>Pre-osteotomy tibial loading (kg)</b>	<b>Post-osteotomy tibial loading (kg)</b>	<b>Pre-osteotomy vs post-osteotomy significance; P</b>
Distal	<b><math>14.32 \pm 0.68</math></b>	<b><math>15.22 \pm 1.47</math></b>	Not significant ( $P=0.20336$ )
Distal	<b><math>12.72 \pm 1.60</math></b>	<b><math>13.68 \pm 1.88</math></b>	Not significant ( $P=0.36328$ )
Proximal	<b><math>20.21 \pm 1.63</math></b>	<b><math>23.14 \pm 1.96</math></b>	Significant ( $P=0.01859$ )
Proximal	<b><math>18.70 \pm 1.30</math></b>	<b><math>21.75 \pm 1.41</math></b>	Significant ( $P=0.00299$ )
At fracture level	<b><math>12.09 \pm 1.14</math></b>	<b><math>13.56 \pm 0.76</math></b>	Significant ( $P=0.02522$ )
At fracture level	<b><math>15.11 \pm 1.69</math></b>	<b><math>17.17 \pm 0.96</math></b>	Significant ( $P=0.02608$ )

The mean percentage increase in tibial loading after a distal osteotomy was 6.9%. One-way ANOVA comparing this to specimens after a proximal or at fracture level osteotomy suggested a significant difference between the means of the three groups (Table 3,  $P= 0.00901$ )

**Table 3**

Percentage increase in midshaft tibial loading with 34kg applied after a fibular osteotomy at three different locations: mean (range)

<b>Distal osteotomy (%)</b>	<b>Proximal osteotomy (%)</b>	<b>At fracture level osteotomy (%)</b>	<b>Proximal vs distal osteotomy significance, P</b>	<b>Proximal vs at fracture level osteotomy significance, P</b>	<b>At fracture level vs distal osteotomy significance, P</b>
6.9 (6.3-7.5)	15.4 (14.5-16.3)	12.9 (12.2-13.7)	Significant ( $P=0.00862$ )	Not significant ( $P=0.20263$ )	Significant ( $P=0.02249$ )

. With the beam structure model adapted for a distal osteotomy (Figure 6A), the midshaft tibial loading was 271N with a sample applied load of 334N (81.1%, Table 4) .

**Table 4**

Calculated midshaft tibial loading with 34kg applied as derived from the beam model.

	Intact fibula	After a distal fibular osteotomy	After a proximal fibular osteotomy
Calculated midshaft tibial force with 334N applied (%)	269N (80.4%)	271N (81.1%)	334N (100.0%)

*After a proximal osteotomy*

After a proximal osteotomy, mean tibial loading in both specimens significantly increased (Table 2,  $P=0.01859$  and  $P=0.00299$ ). Percentage increase in tibial loading after a proximal osteotomy was 15.4%. Tukey's multiple comparison test found this to be significantly different to the percentage increase after a distal osteotomy (Table 3,  $P=0.00862$ ). With the beam structure model adapted for a proximal osteotomy (Figure 6B), the midshaft tibial loading was 334N a sample applied load of 334N (100%, Table 4). This supports the findings from the cadaveric study that a proximal osteotomy leads to the greatest increase in tibial loading (Figure 7).

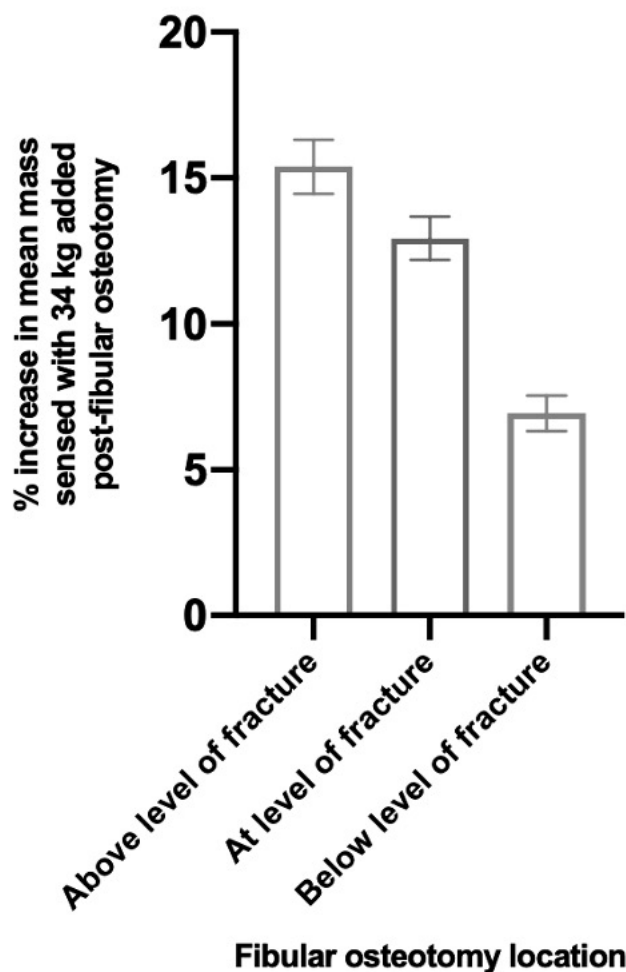


Figure 7 A graph showing the differential effect of osteotomy location on % increase in mean mass sensed in the tibial fracture.

*After an osteotomy at tibial fracture level*

After an osteotomy at tibial fracture level, mean tibial loading significantly increased in both specimens (Table 2,  $P=0.02522$  and  $P=0.02608$ ). Percentage increase in tibial loading after an osteotomy at fracture was 12.9%. Tukey's multiple comparison test found no significant difference between this and the percentage increase after a proximal osteotomy ( $P=0.20263$ ), but found a significant difference when it was compared to the percentage increase after a distal osteotomy (Table 3,  $P=0.02249$ ).

## Discussion

### *Protocol novelty*

The aim of this study was to investigate the optimal location for a fibular osteotomy in the treatment of delayed and hypertrophic non-union of tibial shaft fractures. The bespoke rig and the methodology used to measure axial forces across a tibial fracture were novel in both ease of set-up and use. The minimally invasive force transducer allowed preservation of soft tissues, in contrast to previous studies investigating axial tibial loading which used strain gauges [18] or load cells [19] that necessitated removal of soft tissues or caused significant damage to any tissue retained.

### *A distal osteotomy has minimal effect on compression of the tibia*

In all specimens, there was increased tibial loading with an applied force of 34kg after a fibular osteotomy, supporting the view that the fibula may act as a strut during tibial fracture rehabilitation. However, with a distal osteotomy, the percentage increase in tibial load was smallest out of the three sites (and non-significant). The beam model was designed to explain the experimental findings, with modelled midshaft tibial loading increasing only slightly to 81.1% after a distal fibular osteotomy, compared to 80.4% with an intact fibula. The orientation of the interosseous membrane fibres is likely to be the main contributing factor to these findings. After a distal osteotomy, the applied force could still be transmitted through the fibula proximal to the osteotomy site, but would be transmitted through the interosseous membrane in tension back to the tibia only *distal* to the fracture site, meaning minimal force passes through the midshaft fracture site itself.

### *A proximal osteotomy provides maximal compression to the tibia*

The greatest percentage increase in load through the tibial fracture in specimens was seen after a proximal osteotomy, and this was significantly different to the increase with a distal osteotomy. The experimental findings were supported by the beam model, increasing midshaft tibial loading to 100% after a proximal osteotomy. In contrast to a distal osteotomy, force is transferred back to the tibia from the fibula via the interosseous membrane *proximal* to the midshaft fracture site. As the orientation of the interosseous membrane fibres would prohibit force transmission from the tibia back to the fibula, 100% of the applied force would then pass through the midshaft fracture site. In practice, this would be less than 100% due to the existence of soft tissues, but this model does provide a feasible explanation for the differential effect of fibular osteotomy location on midshaft tibial loading.

### *An osteotomy at fracture level provides greater tibial compression compared to a distal osteotomy*

After an osteotomy at midshaft fracture level, the percentage increase in load through the tibial fracture was between the results with a distal and proximal osteotomy. Whilst the increase in load was significantly different to that with a distal osteotomy, there was no significant difference compared to a proximal osteotomy, which can be attributed to the small sample size of the study. Due to the simplicity of the beam structure representing the interosseous membrane only as a cord and not a sheet, an osteotomy at fracture level was not modelled, but it is reasonable to assume an osteotomy at fracture level would result in more applied load going through the fracture site than a distal osteotomy, but not as much as a proximal osteotomy.

### *Clinical relevance*

In current orthopaedic practice, fibular osteotomies may be used as a second-line intervention in non-union of tibial fractures which had been managed by conservative treatment in plaster, intra-medullary nailing or external fixation [10], and have been shown to result in quicker healing times compared to patients in whom fibulectomies have not been performed [9]. The site of the fibulectomy has never been standardised, with the choice based on a variety of reasons,

including the prevention of ankle instability [20], retaining the option of a future inter-tibiofibular graft [21], and accessibility [22].

The findings from this study indicate that a distal fibular osteotomy does not have a significant impact on tibial loading, and show that a proximal fibular osteotomy is the optimal site. Further studies with a larger sample size are warranted, to investigate if a statistically significant difference exists between proximal and fracture-level osteotomies. The assumption that tibial loading would result in faster healing is based on Wolff's law [23], which states that living bone adapts and strengthens in response to applied forces. Live animal models have shown this to be the case: O'Sullivan et al. [24] demonstrated that increased loading on fractured canine tibiae increased blood flow to the fracture, resulting in increased periosteal and endosteal bone mass compared to controls at 6 and 12 weeks post-fracture. They suggest that adding load improved healing by increasing venous pressure and thus capillary filtration, providing better nutrition to osteogenic cells. Functional weight-bearing in rats was also found to ameliorate the healing rate of femoral fractures when compared to rats that had been immobilised [25].

## **Conclusions**

This study describes a novel method of measuring axial tibial forces, using a minimally invasive approach and a reproducible protocol which could be used for investigation of other long bones. We demonstrated that a fibular osteotomy increases axial tibial loading regardless of location, with the greatest increase after proximal fibular osteotomy. Our simple beam model proposes that a contributing factor to the differential effect of fibular osteotomy location is the oblique orientation of the fibres of the interosseous membrane, which only permits unidirectional force transmission from fibula to tibia. We therefore recommend a proximal fibular osteotomy when it is performed in the treatment of delayed and non-union of tibial midshaft fractures.



## References

- [1] Court-Brown CM, Rimmer S, Prakash U, McQueen MM. The epidemiology of open long bone fractures. *Injury* 1998;29:529–34. [https://doi.org/10.1016/S0020-1383\(98\)00125-9](https://doi.org/10.1016/S0020-1383(98)00125-9).
- [2] Court-Brown CM, Caesar B. Epidemiology of adult fractures: A review. *Injury* 2006;37:691–7. <https://doi.org/10.1016/j.injury.2006.04.130>.
- [3] Larsen P, Elsoe R, Hansen SH, Graven-Nielsen T, Laessoe U, Rasmussen S. Incidence and epidemiology of tibial shaft fractures. *Injury* 2015;46:746–50. <https://doi.org/10.1016/j.injury.2014.12.027>.
- [4] Sarmiento A. A Functional Below-the-Knee Cast for Tibial Fractures. *JBJS* 1967;49:855.
- [5] Brown PW, Urban JG. Early weight-bearing treatment of open fractures of the tibia. An end-result study of sixty-three cases. *J Bone Joint Surg Am* 1969;51:59–75.
- [6] Houben IB, Raaben M, Van Basten Batenburg M, Blokhuis TJ. Delay in weight bearing in surgically treated tibial shaft fractures is associated with impaired healing: a cohort analysis of 166 tibial fractures. *Eur J Orthop Surg Traumatol* 2018;28:1429–36. <https://doi.org/10.1007/s00590-018-2190-2>.
- [7] Charnley J, editor. FRACTURES OF THE SHAFT OF THE TIBIA. The Closed Treatment of Common Fractures. 4th ed., Cambridge: Cambridge University Press; 2003, p. 205–49. <https://doi.org/10.1017/CBO9780511666520.019>.
- [8] Mills LA, Aitken SA, Simpson AHRW. The risk of non-union per fracture: current myths and revised figures from a population of over 4 million adults. *Acta Orthopaedica* 2017;88:434–9. <https://doi.org/10.1080/17453674.2017.1321351>.
- [9] Abadie B, Leas D, Cannada L, Malm P, Morwood M, Howes C, et al. Does Screw Configuration or Fibular Osteotomy Decrease Healing Time in Exchange Tibial Nailing? *J Orthop Trauma* 2016;30:622–6. <https://doi.org/10.1097/BOT.0000000000000647>.
- [10] Rizk A. Partial fibulectomy for treatment of tibial nonunion. *Egypt Orthop J* 2014;49:18–23. <https://doi.org/10.4103/1110-1148.140533>.
- [11] Lifestyles Team, NHS Digital. Health Survey for England 2018 2019.
- [12] Iyaji PI, Alashkham A, Alraddadi A, Soames R. ANATOMICAL STUDY OF THE MORPHOMETRY OF THE ANTERIOR CRUCIATE LIGAMENT ATTACHMENT SITES. Estudio anatómico de la morfometría de los sitios de fijación del ligamento cruzado anterior. *Revista Argentina de Anatomía Clínica* 2016;8:29–37. <https://doi.org/10.31051/1852.8023.v8.n1.14205>.
- [13] Pan N. Length of long bones and their proportion to body height in Hindus. *Journal of Anatomy* 1924;58:374.
- [14] Kimura T. Cross-Section of Human Lower Leg Bones Viewed from Strength of Materials. *Journal of the Anthropological Society of Nippon* 1971;79:323–36. <https://doi.org/10.1537/ase1911.79.323>.
- [15] Evans FG. Mechanical properties and histology of cortical bone from younger and older men. *The Anatomical Record* 1976;185:1–11. <https://doi.org/10.1002/ar.1091850102>.
- [16] Hente R, Cordey J, Perren SM. In vivo measurement of bending stiffness in fracture healing. *Biomed Eng Online* 2003;2:8. <https://doi.org/10.1186/1475-925X-2-8>.
- [17] Bauchau OA, Craig JJ. Euler-Bernoulli beam theory. In: Bauchau OA, Craig JJ, editors. *Structural Analysis*, Dordrecht: Springer Netherlands; 2009, p. 173–221. [https://doi.org/10.1007/978-90-481-2516-6\\_5](https://doi.org/10.1007/978-90-481-2516-6_5).
- [18] Wang Q, Whittle M, Cunningham J, Kenwright J. Fibula and its ligaments in load transmission and ankle joint stability. *Clin Orthop Relat Res* 1996;261–70. <https://doi.org/10.1097/00003086-199609000-00034>.
- [19] Funk JR, Rudd RW, Srinivasan SCM, King RJ, Crandall JR, Petit PY. Methodology for Measuring Tibial and Fibular Loads in a Cadaver. *SAE Transactions* 2002;111:960–9.
- [20] Uchiyama E, Suzuki D, Kura H, Yamashita T, Murakami G. Distal Fibular Length Needed for Ankle Stability. *Foot Ankle Int* 2006;27:185–9. <https://doi.org/10.1177/107110070602700306>.

- [21] Butt MF, Mir BA, Halwai MA, Farooq M, Dhar SA. Partial resection of fibula in treatment of ununited tibial shaft fractures. *Indian Journal of Orthopaedics* 2006;40:247. <https://doi.org/10.4103/0019-5413.34505>.
- [22] Dujardyn J, Lammens JMG. Treatment of delayed union or non-union of the tibial shaft with partial fibulectomy and an Ilizarov frame. *Acta Orthopaedica Belgica* 2007;73:630–4.
- [23] Wolff J. *The Law of Bone Remodelling*. Berlin Heidelberg: Springer-Verlag; 1986. <https://doi.org/10.1007/978-3-642-71031-5>.
- [24] O’Sullivan ME, Bronk JT, Chao EYS, Kelly PJ. Experimental Study of the Effect of Weight Bearing on Fracture Healing in the Canine Tibia: *Clinical Orthopaedics and Related Research* 1994;NA;273–83. <https://doi.org/10.1097/00003086-199405000-00042>.
- [25] Sarmiento A, Schaeffer JF, Beckerman L, Latta LL, Enis JE. Fracture healing in rat femora as affected by functional weight-bearing. *J Bone Joint Surg Am* 1977;59:369–75.