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Original article

Biomechanical investigation into the torsional failure of immature long bone

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ABSTRACT

Approximately 50% of infant and toddler long bone fractures are attributed to non-accidental trauma; however, differentiating from benign mechanisms is subjective, due to an absence of evidence-based diagnostic tools. Previous studies investigated small ranges of rotational velocities in animal long bone models, although did not report the variation in the spiral fracture angle. This study considered the fracture angle as a potential clinical measure, correlating this data with a wider range of rotational velocities. The spiral fracture angle was measured relative to the long axis, whilst noting the narrowest diaphysal diameter, location of the fracture, and the extent of comminution and periosteal disruption. Twenty-six bones failed in spiral fracture, with the potting material failing in the remaining tests. All spiral fractures centred on the narrowest diaphysal diameter. Slower rotational velocities caused fracture angles approaching 45°, whereas fractures at greater velocities caused fracture angles nearer 30°. A relatively strong trend ($R^2 = 0.78$) is reported when the normalised fracture angle (against the narrowest diaphysal dimension) was plotted against the rotational rate. A relationship has been identified between the angle of spiral fracture and the rotational velocity using the immature bovine metatarsal model. This trend forms a scientific foundation from which to explore developing a diagnostic, evidence-based tool that may ultimately serve to assist differentiating between accidental and non-accidental injury.

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1. Introduction

Approximately one half of long bone fractures presented by infants and toddlers are attributed to non-accidental trauma.^{1–6} Whilst guidelines exist to assist clinicians differentiating between accidental and non-accidental injury, the difficulty of achieving a correct diagnosis should not be

underestimated. Spiral fractures, for example, are typically attributed to non-accidental injury; however, these fractures may also result from benign trauma.⁷

Very few studies have investigated the biomechanics of failure in immature bone. Cadaveric studies have reported a difference in biomechanical properties between immature and mature bone, with the former having a lower modulus of

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Fig. 1 – A schematic representation of the experimental setup to apply a torque to the immature bovine long bone.

elasticity, bending strength and mineralisation (i.e. ash content).^{8,9} Pierce et al (2004) has previously explored the validity of the immature porcine femur as a model of a paediatric long bone; however, frequent epiphyseal plate failures meant that spiral fractures were produced in only two of the seven bones.¹⁰

This study investigates whether the appearance of a spiral fracture can be related to the causal mechanism. This hypothesis forms a scientific foundation from which to explore developing a diagnostic, evidence-based tool that may ultimately serve to assist differentiating between accidental and non-accidental injury.

2. Methods

Bovine metacarpal bones ($n = 32$) were harvested from skeletally immature, 7-day-old calves; these bones were freely available as a by-product of the food industry. Sharp dissection was used to remove the overlying soft tissues, whilst ensuring the periosteum remained intact. Each bone was then

macroscopically examined for any damage or previous fracture. The narrowest diaphysal diameter was recorded and the bones divided into 8 groups for testing different applied rotational velocities to failure.

The bones were subjected to a torsional load using a servohydraulic testing machine (MTS 858 Mini Bionix testing machine; Cirencester, UK); this is schematically represented in Fig. 1. The centroidal axis of each bone was identified using a custom-made extra-medullary jig, enabling alignment with the rotational axis of the machine and thereby minimising out-of-plane loading (e.g. bending). An 8 mm hole was drilled at each epiphysal centre of rotation to centralise the bones in the cylindrical housings, before a potting material (Building Adhesives Limited, Stoke-on-Trent, UK) was used to embed the epiphyses and epiphysal growth plates. Each group of potted bones was tested at a specific applied rotational velocity ($0.5, 1, 15, 30, 45, 60, 75, 90^\circ \text{ s}^{-1}$) to failure.

After testing, each fractured bone was manually reduced and then imaged in two perpendicular planes, allowing the spiral fracture angle to be measured at its mid-point relative to the long axis.¹¹ This data is ultimately presented following normalisation against the narrowest diaphysal diameter, to account for the variation in bone geometry throughout the tested cohort. Outcomes were also collected describing the fracture location and the extent of both periosteal disruption and comminution.

3. Results

All 32 bones failed with a spiral fracture; however, 6 tests were excluded due to concurrent potting material failure

Table 1 – Minimum diameter and fracture angle of each bone tested at 8 different rotational velocities.

	Bone 1	Bone 2	Bone 3	Bone 4	Mean
0.5° s^{-1}					
Minimum diameter/mm	18	17	–	16	17
Fracture angle/degrees	47	43	–	39	43
1° s^{-1}					
Minimum diameter/mm	16	18	19	–	18
Fracture angle/degrees	42	42	40	–	41
15° s^{-1}					
Minimum diameter/mm	19	18	20	22	20
Fracture angle/degrees	45	44	41	26	39
30° s^{-1}					
Minimum diameter/mm	23	21	–	21	22
Fracture angle/degrees	42	42	–	37	40
45° s^{-1}					
Minimum diameter/mm	21	19	20	–	20
Fracture angle/degrees	39	37	36	–	37
60° s^{-1}					
Minimum diameter/mm	19	18	–	21	19
Fracture angle/degrees	41	39	–	32	37
75° s^{-1}					
Minimum diameter/mm	19	20	22	–	20
Fracture angle/degrees	37	35	32	–	35
90° s^{-1}					
Minimum diameter/mm	19	18	19	21	19
Fracture angle/degrees	34	34	30	26	31

Fig. 2 – Normalised data (i.e. fracture angle/minimum diameter) plotted against rotational rate of the tested bone specimens. The standard error, regression analysis equation and R^2 value are also displayed.

which may have influenced the fracture angle. All analysed bones demonstrated typical spiral fracture morphology, with the fracture centre at the narrowest diaphysal diameter (Table 1). The majority of fractures were two-part fractures; however, 3 bones tested at the fastest rate of rotation (i.e. 90° s^{-1}) demonstrated failure into more than two pieces, which coincided with periosteal disruption. The data is summarised in Table 1, describing how the mean fracture angle varies from the highest rotational rate (31°) to the slowest rotation rate (0.5° s^{-1} ; 43°). The normalised fracture angles demonstrated a linear trend when plotted against the rotational rate (Fig. 2).

4. Discussion

This study explored the hypothesis that the fracture mechanism influenced the fracture appearance; specifically, the rate of rotation was investigated to determine whether this influenced the fracture angle. A successful protocol was developed that achieved spiral fractures in over 80% of tests, with the angles of the 26 analysed bones reported in Table 1; the unsuccessful tests were due to failure of the potting material. Interestingly, the normalised fracture angles demonstrated a relatively strong correlation with the rotational rate (Fig. 2; $R^2 = 0.78$).

A broad range of rotational velocities were used during the testing protocol, spanning the two velocities previously reported by Aguel.¹² The absence of fracture angles prevents a comparison of our data with Aguel,¹² whilst Sammarco et al^{11,13} did not identify a relationship between fracture angle and rotational velocity. This may, however, be explained by the use of only two, relatively similar rotational velocities. The results of our study do compare favourably with the clinical observations of Johner et al,¹⁴ however, who reported steeper fracture angles in 87% of children injured in high velocity incidents.

The trend presented in this study (Fig. 2) between the normalised fracture angle and the rotational velocity establishes a scientific foundation for further paediatric

investigation. This relationship was identified by adopting a systematic experimental approach, using an immature bovine metacarpal model due to its similar biomechanical properties to paediatric bone.^{8,9} Whilst there are differences in both dimensions and osteon characteristics, the bone geometry minimised non-axis loading and the distribution of the cross sectional area relative to the centroidal axis is symmetric throughout the length of the bone. Applying a predominantly torsional load to the isolated bone enabled an appreciation of this fundamental characteristic.

The relatively thick periosteum, which differentiates immature long bone from adult long bone, was retained in this study (unlike Pierce et al, 2004). Our results would suggest that the periosteum is influential in restraining bone fragments during comminution. Comparison with mature bovine metatarsals indicated that the relative thickness of this tissue is also down-regulated during bovine maturation, which would lead to a likely reduction in its overall strength. Hence, this likely degradation in biomechanical properties could explain the conflicting reports as to whether periosteum has an added mechanical role in the fracture mechanics of long bones.^{15–18}

This study investigated whether the appearance of a spiral fracture can be related to its causal mechanism. A relationship has been established between the rotational velocity of an immature long bone and the subsequent fracture angle. Whilst it is acknowledged that translation to a clinical environment is currently limited, this correlation is encouraging and provides a foundation from which to further explore this relationship. Ultimately, this research aims to develop a diagnostic tool, for use by both clinicians and forensic experts, to assist in the differentiation of accidental and non-accidental injury in the infant and toddler population.

Conflicts of interest

No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

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