Journal of Forensic and Legal Medicine 52 (2017) 5–11

Contents lists available at ScienceDirect

Journal of Forensic and Legal Medicine

journal homepage: www.elsevier.com/locate/jflm

Femur fracture biomechanics and morphology associated with torsional and bending loading conditions in an *in vitro* immature porcine model

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ARTICLE INFO

Article history:
Received 6 May 2017
Received in revised form
21 July 2017
Accepted 24 July 2017
Available online 25 July 2017

Keywords:
Bone
Femur
Fracture
Biomechanics
Animal model
Failure energy

ABSTRACT

Purpose: The objectives of this study were to describe fracture morphology resulting from common loading mechanisms such as bending and torsion in immature bone and to identify differences in the energy required to produce various fracture types under these two loading mechanisms using an immature porcine animal model.

Methods: Twenty-six *in vitro* immature porcine femora were mechanically tested in 3-point-bending and torsion. Femur specimens were tested with and without soft tissue and at both quasi-static and dynamic loading rates. Bone geometry and density measures were determined for each femur using dual-energy x-ray absorptiometry and plain film x-rays. Failure load, stiffness, and energy to failure were determined for each specimen from the load-displacement history from mechanical tests.

Results: 3-point bending tests resulted in 10 transverse fractures and 2 oblique fractures. Torsion tests resulted in spiral fractures. Mean energy required to produce transverse fractures (3.32 Nm) was double that associated with spiral fractures (1.66 Nm). In bending, specimens with soft tissue intact required significantly greater energy to fracture (4.40 Nm) than specimens with soft tissue removed (2.92 Nm). Torsional loading rate did not significantly affect energy to fracture.

Conclusions: Fracture morphology is dependent upon loading conditions. Energy to failure allows for comparison across various loading conditions, and thus offers an effective means of characterizing fracture thresholds for a wide range of scenarios. Consideration should be given to whether or not soft tissue is left intact when conducting experiments using whole bone specimens given its influence on energy to failure.

1. Introduction

Fractures are a common presentation of physical child abuse, occurring in nearly a third of child abuse cases.[1–3] Femur fractures are particularly concerning, accounting for up to 50% of all fractures in child abuse.[4–10] In young, non-ambulating children, fractures are strong indicators of abuse; studies have reported between 30% and 50% of femur fractures in non-ambulating children or those in early ambulating stages are due to abuse.[11–13] However, femur fractures are also a common result of accidental trauma, such as household and playground falls, making diagnosis of abuse particularly difficult. Studies have attempted to characterize and distinguish abusive and accidental femur fractures, but found no significant difference in the type and location of fractures between the two causes. In both abusive and non-abusive trauma, transverse, spiral, and oblique fractures at the mid-diaphysis were the most common, though the relative percentages of these fracture types varied between studies.[6,14–17]

Though fracture type alone may not be an indicator of abuse, evidence suggests that consideration of biomechanical factors in addition to fracture type may improve diagnoses. For example,

Abbreviations: DXA, dual-energy x-ray absorptiometry; BMD, bone mineral density; BMC, bone mineral content; AP, anterior-posterior; ML, medial-lateral; CSA, cross-sectional area.

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http://dx.doi.org/10.1016/j.jflm.2017.07.021
1752-928X/

Pierce et al.[18] attempted to differentiate abusive and accidental femur fractures in children presenting to the Emergency Department with a history of a stair fall. The authors used a multidisciplinary approach to develop an injury plausibility model that accounted for factors such as detail of the provided history, fracture compatibility with dynamics of the provided history, time to seek care, and whether the child had additional injuries. The injury plausibility model was found to be a useful clinical assessment tool and highlighted the need for consideration of biomechanical compatibility to assess whether a femur fracture was the result of abusive or accidental mechanisms.

An understanding of fracture mechanism and biomechanical response of bone is also critical in the determination of abuse vs. accident. That is, what type of loading condition generates a specific fracture morphology (e.g. spiral fracture, transverse fracture, etc.) and what level of loading or energy is required to cause a fracture. Advances in fracture biomechanics of immature bone have been achieved through animal models since the availability of human pediatric bone is limited. For example, using immature ovine tibiae Cheong et al.[19] investigated fracture morphology in 4-point bending and torsional testing at various strain rates, demonstrating a dependency of fracture pattern on strain rate. Pierce et al.[20] found the combination of bone mineral density and geometry to be predictors of fracture load in immature porcine femora tested in 3-point bending. Similarly, Koo et al.[21] found bone mass to be predictive of bone strength using an immature porcine femora model of 3-point bending. Although animal models have limitations, they provide insight as to how immature bone may respond under loading and are key to forensic investigations of fractures in children.

1.1. Aim of work

An improved understanding of the biomechanics of pediatric long bone fractures may aid in differentiating between abusive and accidental injuries. In this study we sought to (1) describe fracture morphology resulting from common loading mechanisms such as bending and torsion in immature bone and (2) to identify differences in the energy required to produce various fracture types under these two loading mechanisms using an immature porcine animal model.

2. Methods

In vitro immature porcine femora were mechanically tested in 3-point-bending and torsion. Femur specimens were tested with and without soft tissue and at both quasi-static and dynamic loading rates (Table 1). This study was approved by the University of Pittsburgh Institutional Animal Care and Use Committee (IACUC #0304451). Pelvic limb specimens were obtained from 13 disease free 3-month-old piglets and stored frozen at −20 °C. Based on radiographic comparison, 3-month-old piglet femora used in this study were found to be comparable to that of 3-year-old children with regards to ossification, and metaphyseal and epiphyseal morphology.

2.1. Specimen preparation

Twenty-six porcine pelvic-limb specimens were thawed to room temperature, then disarticulated at the hip and stifle (knee) joints. For all but 6 specimens, soft tissue was removed from the femur with care taken to leave the periosteum intact. Six specimens were left with soft tissue intact to determine whether soft tissue had an effect on fracture outcome measures. After dissection, femora were wrapped in saline-soaked gauze to prevent dehydration and refrozen (−20 °C) until radiography and mechanical testing.

2.2. Radiographic examination

To ensure that differences in fracture loads and energy were due to differences in loading mechanism and not bone characteristics, bone geometry and density measures were determined for each femur. Dual-energy x-ray absorptiometry (DXA) scans were performed[a] on frozen femora; bone mineral density (BMD) and bone mineral content (BMC) were determined for each entire femur. Femora were then thawed at 4 °C for 24 h. Once thawed, plain x-rays of the femora in the anterior-posterior (AP) and medial-lateral directions (ML) were obtained. Posterolateral and mediolateral mid-diaphyseal inner diameter, outer diameter, and length between proximal and distal growth plates were measured on the x-ray images using calipers. Measurements from the AP and ML views were averaged for each femur specimen. Assuming a circular cross-section, mid-diaphysis cross-sectional area (CSA) was estimated for each specimen. Post-test AP and ML radiographs were also performed following mechanical testing to determine fracture morphology.

2.3. Mechanical testing

All specimens were tested to failure on a servo-hydraulic testing system[b] with a 2-axis 22.2 kN (5000 lb_f; axial force) and 113 Nm (1000 in-lb_f; torque) capacity load cell[c] using custom fabricated test jigs (Fig. 1). A custom data acquisition program[d] was developed to collect applied force/moment data and displacement (angular displacement during torsion and linear translation during bending) of the test system actuator. Data were sampled at 2000 Hz for bending tests and torsion tests conducted at 90 deg/s (high loading rate). A 100 Hz sampling rate was used for torsion testing conducted at 0.17 deg/s (low loading rate). For bending experiments, data were filtered with a cut off frequency of 500 Hz. For torsion experiments, data were filtered with 30 Hz and 0.5 Hz cut off frequencies in experiments using a high loading rate and low loading rate, respectively.

For 3-point-bending, the specimen was oriented such that the actuator component contacted the posterior aspect of the femur (i.e. bending in the sagittal plane). Outer supports were separated 4.45 cm (1.75 in) for all bending tests and the femur was centrally loaded. This value was chosen to ensure supports would be between proximal and distal growth plates. Bending tests were performed for femora with and without soft tissue removed.

For torsion, the proximal and distal ends of the femur were secured in potting blocks using Bondo® automotive body filler. To prevent slipping, 0.159 cm (1/16 in) diameter steel pins were inserted into predrilled holes in the femur approximately 0.635 cm (¼ in) distal to the proximal growth plate and 0.635 cm (¼ in) proximal to the distal growth plate. The ends of the femur were then placed in the Bondo-filled potting blocks (with pins submerged) until fully hardened. The potting blocks interfaced with the testing machine via universal joints to minimize artifact bending from improper alignment and the natural curvature of femur. Post-test radiographs were examined to ensure that fractures did not originate at pin insertion points. Torsion tests were performed at two loading rates with soft tissue removed from all specimens (Table 1).

2.4. Data analysis

Failure load (force or moment at instant of fracture), stiffness, and energy to failure were determined for each specimen from the