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Strain rate dependency of fractures of immature bone

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ABSTRACT

Radiological features alone do not allow the discrimination between accidental paediatric long bone fractures or those sustained by child abuse. Therefore, there is a clinical need to elucidate the mechanisms behind each fracture to provide a forensic biomechanical tool for the vulnerable child. Four-point bending and torsional loading tests were conducted at more than one strain rate for the first time on immature bone, using a specimen-specific alignment system, to characterise structural behaviour at para-physiological strain rates. The bones behaved linearly to the point of fracture in all cases and transverse, oblique, and spiral fracture patterns were consistently reproduced. The results showed that there was a significant difference in bending stiffness between transverse and oblique fractures in four-point bending. For torsional loading, spiral fractures were produced in all cases with a significant difference in the energy and obliquity to fracture. Multiple or comminuted fractures were seen only in bones that failed at a higher stress or torque for both loading types. This demonstrates the differentiation of fracture patterns at different strain rates for the first time for immature bones, which may be used to match the case history given of a child and the fracture produced.

1. Introduction

For immature human bones, it is not possible to differentiate between fractures sustained from child abuse and those caused accidentally solely from radiological features (Leventhal, 1999), even though various injury mechanisms have been proposed (Haney et al., 2009; Pierce et al., 2004). Therefore, there is a clear need to understand paediatric whole bone failure mechanisms (Ebacher et al., 2007; Kress et al., 1995; Ouyang et al., 2003).

Among the many fracture patterns seen clinically, spiral, oblique and transverse long bone fractures are the most common, making it difficult to diagnose non-accidental injury (NAI) in such cases (Caffey, 1946; Carty, 1993). The prospect of using engineering tools to interpret the verbal description of an injury mechanism from either the child or the carer, would allow a level of confidence to be assigned to the described injury mechanism responsible for the observed fracture. It is, therefore, important to be able to link the loading mechanism to the fracture type. In order to achieve this, an experimental method needs to be developed to create a consistent reproduction of relevant fractures. This would then allow their replication in a computer model that could be used as an objective tool to assist in the detection of NAI. This would be especially necessary to prevent situations where NAI is missed, as the child may suffer from further physical and emotional abuse, thereby stunting his/her eventual growth and intellectual and emotional development, or even resulting in death (Jayakumar et al., 2010; Stotts, 2007). Conversely, a wrongful accusation of innocent families may lead to the unwarranted separation of the family and child (Kowal-Vern et al., 1992; Pierce and Bertocci, 2008).

There are only three studies that have investigated the fracture tolerance of the immature population using whole bones, namely that by Forman et al. (2012) and Ouyang et al. (2003) for humans, and Pierce et al. (2000) for pigs. However, the latter is the only work in the literature that had the intended aim of reproducing fractures seen in child abuse (Pierce et al., 2000). Porcine femora were used in their study, where the age equivalence of the specimens assumed that one week in pigs is approximately equivalent to a year in humans (Baumer et al., 2009). Their experiments were conducted at rates of 1 mm/s for three-point bending and 1 $^{\circ}s^{-1}$ for torsional loading. These fall under the quasi-static strain rate regime (Cristofolini et al., 2010), which is too low to reproduce injuries caused during child abuse, as they usually happen at higher loading rates (Miltner and Kallieris, 1989).

Three-point bending has been the test of choice, because it is able to model the event when a bone is impacted by an object (Pierce et al., 2000); this is a known mechanism of injury in child abuse (Hobbs, 1989). Yet, unlike the consistent transverse fractures reported by Pierce et al. (2000) in all 12 immature porcine femora at low strain

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rate, Forman et al. (2012) reported that fractures in the immature population were rarely initiated at the mid-diaphysis at high strain rates. Instead, oblique or comminuted fractures ensued from cracks that were initiated off-centre. The presence of multiple types of fracture patterns is consistent with the study conducted by Kress et al. (1995), who impacted 253 tibiae and 136 femurs from the geriatric population at a high velocity of 1.2–7.5 ms^{-1} and found comminuted butterfly fractures and oblique fractures to be the most common. Unfortunately, no fracture patterns were available from the study by Ouyang and colleagues (2003) at both low and high strain rates as the tests were terminated when the slope of the force-time curve dropped to zero. Therefore, the generation of a consistent fracture pattern at high strain rate has not been confirmed.

The three-point bending test poses problems, because the curvature and variation in cross-section of long bones along their length may cause high shear stress at the mid-length of the specimen during testing, where it is most likely to fail. The complex geometry of bone also increases the possibility of the specimen failing in shear rather than in tension, which makes the analysis of the failure more difficult. Moreover, it has been recommended that the specimens used in three-point bending tests should be straight and have a uniform cross-section (Athanasiou et al., 2000). Thus, four-point bending tests are more suited to study the case of bending as the middle section of the bone would experience a constant bending moment, thus resulting in pure direct stress for a bone of constant, symmetrical, cross section, but these tests have not been conducted on immature bone.

Spiral fractures have been consistently produced in all the works involving torsion of intact whole mature bones. Torsional loading of sheep femora produced spiral fractures in the mid-diaphysis consistently in the work of Wullschleger (2010). A combination of longitudinal and spiral fractures was reported by Taylor et al. (2003), who tested mature chicken metatarsals to failure using torsional cyclic testing at 3 Hz. It is therefore interesting to note that testing of immature porcine femur at a rate of 1 $°s^{-1}$ failed to generate a spiral fracture consistently (Pierce et al., 2000). Despite attempts made to reduce the working length of the specimens, growth plate separation continued to be the dominant failure mode. Spiral fractures have also been produced in the three-point bending work of Kress and co-workers (1995), who noted the correlation with the presence of a torsional load, yet perhaps this is also due to the presence of shear stress in combination with direct stress, producing a principal direct stress oblique to the bone long axis. However, the failure to generate consistent spiral fractures in immature bone further compounds the problem by questioning when spiral fractures, which are seen commonly among children (Hobbs, 1989), are produced.

The aims and objectives of this paper were to design an experimental apparatus to enable testing of immature long bones in bending and torsion, characterise the mechanical behaviour of immature bone to the point of failure at multiple strain rates, and to investigate if consistent fracture patterns are produced in bending and torsion across strain rates.

2. Materials and methods

Twenty ovine tibiae from 5 months old British Texel lambs were harvested after slaughter. A month in sheep corresponds to a year in human (Nafei et al., 2000). Ovine tibia has a similar aspect ratio to human tibia and the former can be considered similar to the latter but scaled down by a third (Finlay et al., 1995; Osterhoff et al., 2011). Four bones were used for each set of experiments: two torsional loading experiments and three four-point bending tests. The bones were cleaned of all soft tissues, leaving the periosteum intact as far as possible, before they were wrapped in cloth soaked in 1% Phosphate Buffered Solution (PBS). The bones were then double bagged and frozen at -20 °C for storage, as the strength of the bone has been found to remain unchanged by the process of freezing (Moreno and Forriol, 2002). The bones were stored for a maximum of one year and they were defrosted in a cool box in their sealed bags 6 h prior to the start of mechanical testing. The bones were kept hydrated by misting them with water every 5 min. Strain gauges were affixed for a computational study; these results are not presented here.

2.1. Image acquisition and specimen alignment

Thawed bones underwent micro-CT scanning with the tissue paper intact in a Metris X-Tek HMX ST 225 CT System (Nikon Metrology, Tring, UK). A 1 mm copper filter was used as the reflection target, with a focal spot size of 5 μm and the X-rays were set at 200 kV and 200 μA. A resolution of 115 μm was achieved. The 3D reconstructions of the scans were used to generate solid models for geometrical analysis to align the specimens.

The landmarks used to align the bone in four-point bending and torsion were calculated from a specimen-specific alignment system (Cheong and Bull, 2015). In brief, this methodology optimised bones to experience *near* pure shear, and *near* pure direct stress in torsion and bending, respectively. This was achieved via the solid mechanics principles that: for any object, there exists a set of principal axes where the structure would experience maximum and minimum stresses; pure torsion produces pure shear in a perfectly symmetrical structure; and four point bending produces a pure bending moment with no shear stresses within the inner span in a symmetrical structure. The results of the geometrical analysis were used to determine the distances between the rollers in four-point bending, and the level of fixation of bones for torsion. In all cases the 4:1 width-to-span ratio for simple bending and torsion, as found by Hardy and Pipelzadeh (1991), who found that this was the minimum required to prevent deep flexion, was maintained.

2.2. Mechanical testing

The tests were conducted on an Instron 8874 universal materials testing machine (Instron – Division of ITW Limited, High Wycombe, UK), using linear displacement or angular control. The synchronous recording of forces, torques, translations and rotations was achieved via a custom-written LabVIEW program, which also controlled the actuator of the Instron machine and obtained data at 0.2 ms intervals. The process of fracture propagation was captured by a high-speed video camera (Phantom v126, Vision Research, Wayne, NJ, US). A frame rate of 7000–10000 fps was used depending on the actual frame of view and lighting conditions. The fracture morphology was classified based on the crack initiation observed in the high-speed videos.

To characterise the structural behaviour of ovine tibiae, four-point bending tests to failure were conducted at three different loading rates: 50 mm/s ($\dot{\epsilon}$: 0.1–0.3 s^{-1}), 25 mm/s ($\dot{\epsilon}$: 0.08–0.1 s^{-1}), and 1 mm/s ($\dot{\epsilon}$: 0.003–0.004 s^{-1}), using the specimen-specific alignment system. All the bones were tested in the sagittal plane, with the posterior side of the bone in tension, using a custom-made jig to minimise the transmission of unintended forces and torques (Fig. 1). Two rounds of preconditioning were conducted before testing the bone to failure. Each specimen was preconditioned by loading at a constant velocity of 0.5 mm/s until the crosshead moved 1.5 mm. The bone was then unloaded at a speed of 0.01 mm/s, followed by an interval of 5 min before the next run took place. For failure testing, loading was halted when a displacement of 4 mm was reached (5 mm for the slowest tests), which was determined from a pilot test to be the limit to cause fractures.

For torsional loading, 16 right tibiae were used with the proximal part externally rotated relative to the distal part. The bones were potted in stainless steel pots using Polymethyl Methacrylate (PMMA) bone cement (Simplex Rapid, Austenal Dental Products Ltd, UK). The distal pot was then attached to a rocker base, which had ball bearings attached to it to allow it to slide on an XY table, which eliminated the transmission of unintended forces to the bone (Fig. 1); the absence of a

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