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Research Paper

Fracture patterns of the growth plate and surrounding bone in the ovine knee joint at different ages

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ARTICLE INFO

Article history:
Received 22 April 2013
Received in revised form
4 September 2013
Accepted 6 September 2013
Available online 18 September 2013

Keywords:
Growth plate
Fracture
Age
Bone
Cartilage

ABSTRACT

Fractures of the growth plate region were performed with cadaver specimens obtained from the ovine distal femur and proximal tibia. Specimens of 6 different ages, ranging from 1 week to 4 years, were investigated in order to determine changes in the fracture characteristics. Mechanical properties (crack resistance and notch tensile strength), supported by microscopy of the distal tibia (thickness of growth plate and its zones, trabecular bone volume ratio) were determined. The crack propagated through different regions depending on age, which was observed both in microscopy and mechanical tests. In specimens of younger animals the fracture typically went through trabecular bone, often parallel to the growth plate, and only sometimes through the growth plate cartilage. Specimens of older animals fractured directly through the growth plate cartilage, while trabecular bone was not affected at all. Adult specimens had significantly higher mechanical values than the young ones. The results reveal the underlying mechanical properties that induce different fracture patterns of the epiphyseal growth plate at different stages of growth. The possibility of fractures through trabecular bone parallel to the growth plate in newborns and infants should be considered when clinical radiographs of paediatric fractures are analysed and classified.

1. Introduction

The most significant difference between the immature and the mature adult skeleton is the presence of an epiphyseal growth plate. The epiphyseal growth plate is a layer of proliferating, growing and ossifying cartilage situated on both ends of long bones, between the trabecular bone of epiphysis and metaphysis. It is the origin of longitudinal bone growth (Milz et al., 2002; Villemure and Stokes, 2009). But it is also a weak point, where many fractures can occur at any

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http://dx.doi.org/10.1016/j.jmbbm.2013.09.010

age before physeal closure. These fractures were initially listed and classified systematically by Salter and Harris (1963). Modern classification differentiates between physeal separations with and without the metaphyseal wedge and contrasts them with epiphyseal fractures, which represent articular injuries with fracture lines crossing all layers of the physeal plate (von Laer et al., 2007). Similar criteria were determined in Peterson's (1994) classification. A modern comprehensive classification of paediatric long bone fractures, which includes diaphyseal, metaphyseal, and epiphyseal fractures, was presented by the AO foundation (Association for the Study of Internal Fixation) (Slongo and Audigé, 2007).

Epidemiological data reflect that 15% to 30% of all skeletal injuries in children involve the physis (Mann and Rajmaira, 1990; Mizuta et al., 1987; Ogden, 1982; Greenfield, 1996). Approximately 80% of physeal injuries occur between the ages of 10 and 16 years (Rogers, 1970; Peterson and Peterson, 1972), with a peak age for physeal separation between the 12th and 13th year of life (von Laer et al., 2007; Barmada et al., 2003; Spiegel et al., 1978; Weinberg and Tscherne, 2006). In contrast, metaphyseal fractures were the predominant lesion among younger children with a median age of 5 years (Skak et al., 1987).

Numerous biomechanical research publications were performed to acquire more knowledge about these epidemiological findings. Chung et al. (1976) subjected whole femoral heads of different ages to shear forces and observed an age dependency of the fracture patterns. The age influence was also reported by Williams et al. (2001) in tensile testing on bone-cartilage-bone slices. They found larger ultimate stress and strain in the thinner growth plates of the older of the two investigated groups. Guse et al. (1989) found that longitudinal nominal stress increases with age in rabbits. Many other studies exist on the shear (Lee and Pelker, 1985; Williams et al., 1999), tensile (Cohen et al., 1992; Fujii et al., 2000), compression (Villemure et al., 2007; Sergerie et al., 2009; Amini et al., 2010; Grover et al., 2007) and indentation (Radhakrishnan et al., 2004) properties of the growth plate. Several clinical studies (Eid and Hafez, 2002; Weinberg et al., 2005) have also been conducted.

The present study aimed to gain pivotal insights into physeal and metaphyseal fracture patterns in different age groups. The wedge splitting method after Tschegg (1986, 1991, 2012a; OENORM B 3592) was performed on specimens from the distal femur and proximal tibia Fracture mechanical data were determined: crack resistance G_F and notch tensile strength σ_{NT}, along with microscope observation of the cracking and morphological characteristics such as thickness and trabecular bone volume fraction.

To the authors' knowledge, no experimental, age-dependent studies on those fracture mechanical properties (crack resistance and notch tensile strength) had been performed in the past. There is a theoretical work by Gómez-Benito et al. (2007) which presented a damage model for the growth plate and calculated the critical failure energy per unit area, a value comparable to the crack resistance. However, they could only compare their result to experimental data obtained in tensile tests, where the post-yield behaviour of the crack was not considered. Knowledge of the total specific fracture energy G_F can help to verify such computational models and to create new models. The data are also important for the bio-engineer and surgeon, to establish whether a fracture runs through bone or through the growth plate, and to determine the forces which lead to a fracture.

2. Materials and methods

2.1. Mechanical testing

2.1.1. Sample preparation for mechanical testing

Left and right proximal tibia and distal femur from 6 different animals (Table 1) were obtained from the Styrian Sheep and Goat Breeding Association. The bones were fresh frozen and stored in NaCl solution at $-20\,^{\circ}$C. The influence of freezing on the mechanical properties was assumed to be negligible (Lee and Pelker, 1985; Stok and Oloyede, 2007). The longest storage time was 4 months. Prior to testing, the bones were thawed to 22 °C. Specimens were cut with a band saw (Metabo BAS 260 Swift) as parasagittal slices between the condyles (Fig. 1) with thickness varying between 5.2 mm and 12.0 mm. A starter notch was cut in with the band saw and ground with abrasive paper in order to smoothen the sharp corners. Then a small sharp notch was incised with a razor blade along the middle of the epiphyseal plate, or in the middle of the notch if there was only trabecular bone (Tschegg et al., 2012a).

The specimens were attached to the wedge split device by screw-clamps and additionally glued with bone cement (Palacos® LV, Heraeus). After 40 min of curing in a moist environment, displacement markers were attached to the specimens, which were then placed in the machine for testing. Fig. 1 displays the specimen and the testing setup.

2.1.2. The wedge splitting method after Tschegg

For a detailed description of this testing method, see the literature (Tschegg 1986, 1991; OENORM B 3592). It was performed on ovine growth plates and on horse bone by Tschegg et al. (2012a, 2012b).

Fig. 1 is a schematic drawing of the setup. Basically, the vertical force of the testing machine was transformed through

Table 1 – Origin and details of the specimens. BV/TV is the estimated bone volume/tissue volume fraction on the epiphyseal and metaphyseal side of the growth plate.

Age [days]	Sex	Breed mother/father	Mass [kg]	Physis thickness [mm]	~BV/TV epi/meta [%]
6 (1 week)	m	Merino/Texel	3	0.86	33/24
45 (1.5 months)	f	Merino/Schwarzkopf	6	0.37	22/33
105 (3.5 months)	f	Merino/Texel	42	0.36	42/62
203 (7 months)	m	Merino/Schwarzkopf	56	0.29	37/62
1473 (4 years)	f	Merino/Merino	70	–	
2567 (7 years)	f	Merino/Merino	60	–	