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The human proximal femur behaves linearly elastic up to failure under physiological loading conditions

Mateusz Maria Juszczyk [a], Luca Cristofolini [a,b,*], Marco Viceconti [a]

[a] Laboratorio di Tecnologia Medica, Istituto Ortopedico Rizzoli, Bologna, Italy
[b] Facoltà di Ingegneria, Università di Bologna, Italy

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ABSTRACT

It has not been demonstrated whether the human proximal femur behaves linearly elastic when loaded to failure. In the present study we tested to failure 12 cadaveric femurs. Strain was measured (at 5000 Hz) on the bone surface with triaxial strain gages (up to 18 on each femur). High-speed videos (up to 18,000 frames/s) were taken during the destructive test. To assess the effect of tissue preservation, both fresh-frozen and formalin-fixed specimens were tested. Tests were carried out at two strain-rates covering the physiological range experienced during daily motor tasks. All specimens were broken in only two pieces, with a single fracture surface. The high-speed videos showed that failure occurred as a single abrupt event in less than 0.25 ms. In all specimens, fracture started on the lateral side of the neck (tensile stress). The fractured specimens did not show any sign of permanent deformation. The force–displacement curves were highly linear ($R^2 > 0.98$) up to 99% of the fracture force. When the last 1% of the force–displacement curve was included, linearity slightly decreased (minimum $R^2 = 0.96$). Similarly, all force–strain curves were highly linear ($R^2 > 0.98$ up to 99% of the fracture force). The slope of the first part of the force–displacement curve (up to 70% fracture force) differed from the last part of the curve (from 70% to 100% of the fracture force) by less than 17%. Such a difference was comparable to the fluctuations observed between different parts of the curve. Therefore, it can be concluded that the proximal femur has a linear-elastic behavior up to fracture, for physiological strain-rates.

1. Introduction

The strain distribution and strength of the proximal human femur has been extensively investigated in the past, both *in vitro* (Keyak et al., 2001; Bessho et al., 2007; Cristofolini et al., 2009) and with numerical models (Lotz et al., 1991; Ota et al., 1999; Schileo et al., 2007). One of the open questions concerns the linear (or the lack of linear) behavior of the femur. In fact, assessment of the linear behavior would improve the understanding of the etiology of femoral fractures (Cristofolini et al., 2010). Furthermore, because of the increasing use of Finite Element (FE) models of the human femur, it would be essential to include the most appropriate rheological model (whether linear-elastic, or elasto-plastic).

In many cases, bone is modeled as a linear-elastic material (Carter and Spengler, 1978; Yosibash et al., 2007; Helgason et al., 2008). In fact, it has been reported that in tension cortical bone tissue exhibits a linear-elastic behavior up to failure (Carter and Spengler, 1978; Fung, 1980), while post-yield nonlinearity is observed in compression (Keller, 1994). Kopperdahl and Keaveny (1998) and Keaveny (1994) reported a linear pre-yield behavior for the trabecular bone, followed by a plastic deformation both in tension and compression (such a post-yield nonlinearity was much less pronounced in tension).

Yield of bone tissue has sometimes been described as an arbitrary point in the stress–strain curve where nonlinearity appears (Hvid and Jensen, 1984) or as a point at which permanent deformation occurs (An and Draughn, 1999). A mechanistic model (Yeni and Fyhrie, 2003) has shown that bone nonlinearity, which is sometimes referred to as post-yield behavior, can be explained by collagen–fiber-bridged microcracks rather than by real plastic post-yield phenomena, as (Keaveny et al., 1994) previously suggested based on *in vitro* tests.

A combination of tension and compression is present in the femoral neck for most loading conditions. As it is impossible to

Abbreviations: BL, biomechanical length of the femur; BW, body weight; CT, computed tomography; DEXA, dual energy X-ray absorptiometry; FE, finite element; HD, diameter of the head of the femur; R^2, coefficient of determination for a linear regression; VPH-OP, Virtual Physiological Osteoporotic Human Project (http://www.vphop.eu/)

* Corresponding author at: Laboratorio di Tecnologia Medica—Istituto Ortopedico Rizzoli, Via di Barbiano, 1/10, 40136 Bologna, Italy. Tel.: +39 051 63 66 864; fax: +39 051 63 66 863.
E-mail addresses: cristofolini@tecno.ior.it, tecno@tecno.ior.it (L. Cristofolini).

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Table 1
Summary of the literature reporting *in vitro* destructive tests where the proximal femur was loaded in a quasi-axial loading configuration. The loading rate (time required to fracture the specimen) and the direction of the applied force (angle between the femoral diaphysis and the force on the femoral head) are reported for each reference. Also indicated is the number of specimens tested and the gender and age of donors. The description of the fracture mechanism is either based on the description provided in the text, or on the pictures and plots available in the manuscript.

Reference	Load rate/time required to induce fracture	Direction of applied force	Specimens: number (preservation)	Gender, age of donors	Fracture mechanism
Alho et al. (1988)	66–390 s (1)	0° in frontal plane 0° in sagittal plane	36 (preservation not specified)	18 female, 18 male 57–87 years old	In most femurs the load–deflection curve was relatively linear, had a gradual curving without any yielding point. A yielding point was identified only in few cases
Augat et al. (1996)	1.0 mm/s (time to fracture of the order of 10–20 s (1))	0° in frontal plane 0° in sagittal plane	20 (formalin fixed)	13 female, 7 male 66–100 years old	Neck (n=18) and trochanteric fractures (n=2). Presence/lack of linearity was not expressly reported
Bessho et al. (2007)	180 s (1)	20° in frontal plane 0° in sagittal plane	11 (fresh-frozen)	6 female, 5 male 52–85 years old	Fluctuations in the force–displacement curve. The yield point indicated in the plot corresponds to 80% of the failure load. The entire curve fits within a band that is narrower than 10% of the failure load
Dalen et al. (1976)	10 s (1)	0° in frontal plane 0° in sagittal plane (plastic block around the specimen up to lesser trochanter)	61 (fresh)	54 female, 7 male 67–80 years old	Linear-elastic plot with small decrease of slope in the upper 30% of the force–displacement curve
Delaere et al. (1989)	2.0 mm/s (actual time to fracture not indicated)	25° in frontal plane 0° in sagittal plane	20 pairs (dried macerated)	Male+female 57–89 years old	Not reported
Keyak (2001), Keyak et al. (2001)	0.5 mm/s (time to fracture of the order of 10–20 s (1))	20° in frontal plane 0° in sagittal plane	18 (fresh-frozen)	10 female, 8 male 52–92 years old	Subcapital and oblique transcervical fractures parallel to the shaft. Presence/lack of linearity not expressly reported. The force–displacement plot in Keyak (2001) is linear, with a two-step fracture
Link et al. (2003)	"stepwise" (actual rate not specified)	11° in frontal plane 0° in sagittal plane	31 (fresh-frozen)	14 female, 17 male 29–91 years old	Linear-elastic up to failure
Lochmüller et al. (1998)	1.0 mm/s (load cycles of increasing magnitude)	0° in frontal plane 0° in sagittal plane	58 (formalin fixed)	24 female, 34 male 57–100 years old	Trochanter (n=10) and neck fractures (n=48). Presence/lack of linearity was not expressly reported
Lochmüller et al. (2002)	6.5 mm/s (time to fracture of the order of 1–3 s (1))	0° in frontal plane 0° in sagittal plane	103 (alcohol/ formalin fixed)	62 female, 41 male 46–97 years old	Trochanter (n=10) and neck fractures (n=83). Presence/lack of linearity was not expressly reported
Lotz et al. (1991)	Not indicated	0° in frontal plane 0° in sagittal plane	1 (fresh-frozen)	Female 66 years old	The load–displacement plot shows fluctuations, including a slight decrease of slope at 50% of the failure load. The entire curve fits within a band as wide as approximately 10% of the failure load
Ota et al. (1999)	0.5 mm/s (time to fracture of the order of 10–20 s (1))	20° in frontal plane 0° in sagittal plane (2)	1 (formalin fixed)	1 male 76 years old	Base-of-the-neck fracture, parallel to the shaft. Presence/lack of linearity was not expressly reported
Yosibash et al. (2010)	26 s (1)	0° in frontal plane 0° in sagittal plane	1 (fresh-frozen)	Male 30 years old	One step fracture following limited post-elastic nonlinearity (5% decrease of linear slope occurred at 67% of maximum force)

Notes:

(1) Time required to fracture the femur specimens was not expressly indicated in the manuscript. The value reported was estimated based on the plots/tables.
(2) Direction of the applied force not specified: the angle was estimated based on the published pictures.