ELSEVIER

Journal of Biomechanics 41 (2008) 356–367

JOURNAL OF BIOMECHANICS

www.elsevier.com/locate/jbiomech
www.JBiomech.com

Subject-specific finite element models implementing a maximum principal strain criterion are able to estimate failure risk and fracture location on human femurs tested *in vitro*

Enrico Schileo[a,*], Fulvia Taddei[a], Luca Cristofolini[a,b], Marco Viceconti[a]

[a]*Laboratorio di Tecnologia Medica, Istituti Ortopedici Rizzoli, Via di Barbiano 1/10, 40136 Bologna, Italy*
[b]*Engineering Faculty, University of Bologna, Italy*

Accepted 2 September 2007

Abstract

No agreement on the choice of the failure criterion to adopt for the bone tissue can be found in the literature among the finite element studies aiming at predicting fracture risk of bones. The use of stress-based criteria seems to prevail on strain-based ones, while basic bone biomechanics suggest using strain parameters to describe failure. The aim of the present combined experimental-numerical study was to verify, using subject-specific finite element models able to accurately predict strains, if a strain-based failure criterion could identify the failure patterns of bones.

Three cadaver femurs were CT-scanned and subsequently fractured in a clinically relevant single-stance loading scenario. Load-displacement curves and high-speed movies were acquired to define the failure load and the location of fracture onset, respectively. Subject-specific finite element models of the three femurs were built from CT data following a validated procedure. A maximum principal strain criterion was implemented in the finite element models, and two stress-based criteria selected for comparison. The failure loads measured were applied to the models, and the computed risks of fracture were compared to the results of the experimental tests.

The proposed principal strain criterion managed to correctly identify the level of failure risk and the location of fracture onset in all the modelled specimens, while Von Mises or maximum principal stress criteria did not give significant information. A maximum principal strain criterion can thus be defined a suitable candidate for the *in vivo* risk factor assessment on long bones.

Keywords: Subject-specific finite element models; Maximum principal strain; Failure criteria; Bone biomechanics; *In vitro* failure tests; Experimental validation

1. Introduction

In general, the strength of a whole bone can be characterised through internal (shape, bone tissue distribution and bone tissue properties) and external determinants (namely, the loading conditions) (Cody et al., 1999). The development of subject-specific finite element (FE) models from computed tomography (CT) data is a powerful tool to non-destructively investigate bone strength *in vivo*: actually, subject-specific FE models are capable to include most of the internal parameters which contribute to bone strength and simulate the influence of general and variable external boundary conditions (Taddei et al., 2003, 2006). Hence, in principle, subject-specific FE models of bones could be able to predict a fracture risk of a specific bone segment under any generic loading condition (i.e., a measure of how far the structure is from failure). However, this is still an open challenge.

So far, it has been proven that FE models perform better than densitometric measurements in the explanation of the failure load variability among different subjects (Cody et al., 1999; Crawford et al., 2003), and consistent results have been achieved in the prediction of the bone strength, but only under a specific loading condition (Keyak et al., 2005). These models may be prospectively useful in all

*Corresponding author. Tel.: +39 051 6366864; fax: +39 051 6366863.
E-mail address: schileo@tecno.ior.it (E. Schileo).

0021-9290/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jbiomech.2007.09.009

cases where a comparative study is needed (e.g., screening of a target population, as osteoporotic subjects, against an average population (Testi et al., 2002), or to evaluate a pharmacological treatment (Cody et al., 2000)). Their principal limitation is however the lack of generality. In fact, their aim was either to replicate the load-displacement curve obtained in an experimental test (Keyak, 2001; Keyak et al., 2005), or to predict the experimentally determined failure load as a function of the global model stiffness (Cody et al., 1999; Crawford et al., 2003). In any case, the simulation strategies adopted were strongly linked to the specific loading condition applied in the experimental tests. More general models are needed to predict and localise the fracture risk for a bone segment under a generic loading condition (e.g., including muscles). This implies implementing a bone tissue failure criterion and a structural collapse criterion. Several authors addressed this issue, but many of them did not include a validation against experimental tests (Ford et al., 1996; Oden et al., 1999; Pietruszczak et al., 1999; Taddei et al., 2003), which is a mandatory step for clinical consideration (Viceconti et al., 2005). Some studies reported a comparison with experimental measurements (Gomez-Benito et al., 2005; Keyak and Rossi, 2000; Keyak et al., 1998; Lotz et al., 1991a, b; Ota et al., 1999). However, no conclusive answer on the methodology to apply can be derived from those works: in (Gomez-Benito et al., 2005) FE and experimental results could not be compared on a specimen basis since only one model was used to represent a cohort of experimentally tested femurs; in (Keyak et al., 1998; Ota et al., 1999) the failure load prediction significantly underestimated the actual values; in (Lotz et al., 1991a, b) the failure load was quite accurately predicted but neither the fracture location nor the failure behaviour were correctly identified when a linear model was used; the non-linear modelling procedure (Lotz et al., 1991b) succeeded in capturing also the actual failure patterns but relied on a targeted CT-scanning procedure, which included the specimen rotation during the CT scan so as to align the femoral axis and the CT-scan axis, and is therefore not clinically applicable.

These studies, irrespectively of the modelling strategies adopted, differed in the specific strength criterion chosen for the bone tissue, that was however almost always based on stress parameters. Keyak (2001) and Keyak et al. (1998, 2005) applied a distortional energy (von Mises stress) criterion. Lotz et al. (1991a, b) used a von Mises stress yield criterion for cortical bone in conjunction with an Hoffmann stress criterion, or a more complicated crushing-cracking stress criterion for trabecular bone. Ota et al. (1999) adopted a principal stress criterion. Finally, Gomez-Benito et al. (2005) proposed an anisotropic stress criterion including fabric tensor information. Only two validation studies on whole bones investigated the possibility of applying strain-based criteria and compared their performance with stress-based ones (Keyak and Rossi, 2000; Lotz et al., 1991a). The outcomes were discordant: in (Lotz et al., 1991a) the adoption of a von Mises strain criterion improved the predictions, with respect to a Von Mises stress criterion; in (Keyak and Rossi, 2000), the strain criteria tested (Von Mises and maximum principal) led to worse accuracy with respect to the homologous stress criteria.

Recent advances in basic bone biomechanics proved the effectiveness of strain-based criteria to describe yield or failure of bone tissue (at least in normal bone, showing normal degree of mineralisation and no genetic alterations): bone failure has been shown to be driven by deformation (Nalla et al., 2003; Taylor, 2003), there is a growing consensus on the substantial isotropy of yield strain and on its invariance to density (Bayraktar et al., 2004b; Chang et al., 1999; Cowin and He, 2005; Currey, 2004; Kopperdahl and Keaveny, 1998), and a strain-based criteria managed to well fit mono- and multi-axial experimental data (Bayraktar et al., 2004a). Thus, it seems advisable to implement strain-based criteria in FE models of bone for the prediction of fracture risk. The discordant results found for strain-based criteria performance in Keyak and Rossi (2000) and Lotz et al. (1991a) may be explained by the limited strain prediction accuracy of the models used ($R^2 < 0.7$), that may have hindered a correct evaluation of strength criteria. Therefore, there is the need to compare the performance of stress and strain-based criteria in an independent study on validated FE models. In a former study, the authors have developed a subject-specific modelling procedure capable to accurately predict ($R^2 = 0.91$, regression slope $= 1.01$, root mean square error $= 10\%$) strain levels in long bones under a variety of loading conditions (Schileo et al., 2007).

The aim of the present work is to verify the possibility of using a maximum principal strain criterion to identify fracture patterns in the framework of an automatic modelling procedure for subject-specific FE models of bones, and compare its performance with two stress-based criteria derived from the literature. This aim was pursued by comparing the results of previously validated subject-specific FE models with measurements obtained on three cadaver femurs loaded to fracture *in vitro* under a loading scenario aimed at replicating spontaneous fractures (Cristofolini et al., 2007).

2. Materials and methods

2.1. Specimen details and diagnostic assessments

Three cadaver femurs, harvested fresh (Table 1), were obtained (IIAM, Jessup, PA, USA) (preserved wrapped in a cloth soaked with physiological solution throughout all the experimental tests and kept at $-25\,^{\circ}C$ when not in use (Evans, 1973)).

All the specimens were CT-scanned (HiSpeed, GE Co., USA) (Table 2) and subjected to dual energy X-ray absorptiometry (DEXA) (Eclipse, Norland Co., USA). They fell in the range from osteopoenia to severe osteoporosis (AJM, 1991) (Table 1).