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Research Paper

An interface finite element model can be used to predict healing outcome of bone fractures

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J.A. Alierta[a], M.A. Pérez[b], J.M. García-Aznar[b,*]

[a]Escuela Politécnica Superior del Ejército, Ministry of Defense, Madrid, Spain
[b]Mechanical Engineering, Aragón Institute of Engineering Research (I3A), University of Zaragoza, Ed. Betancourt-Campus Río Ebro, C/María de Luna, 50018 Zaragoza, Spain

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ABSTRACT

After fractures, bone can experience different potential outcomes: successful bone consolidation, non-union and bone failure. Although, there are a lot of factors that influence fracture healing, experimental studies have shown that the interfragmentary movement (IFM) is one of the main regulators for the course of bone healing. In this sense, computational models may help to improve the development of mechanical-based treatments for bone fracture healing. Hence, based on this fact, we propose a combined repair-failure mechanistic computational model to describe bone fracture healing. Despite being a simple model, it is able to correctly estimate the time course evolution of the IFM compared to in vivo measurements under different mechanical conditions. Therefore, this mathematical approach is especially suitable for modeling the healing response of bone to fractures treated with different mechanical fixators, simulating realistic clinical conditions. This model will be a useful tool to identify factors and define targets for patient specific therapeutics interventions.

1. Introduction

Fractures are a common orthopedic problem and the fracture healing is a natural process that regenerates bone to its original state and function. Several factors influence these bone healing events, such as genetic, cellular and biochemical factors, blood supply, neural and hormonal regulation, age, the type of fracture interfragmentary motion and fracture geometry (Einhorn, 2005; Goodship et al.,1993; Hadjiargyrou et al., 1998; Jagodzinski and Krettek, 2007; Marsell and Einhorn, 2011). However, the most common orthopedic treatments consist on the mechanical stabilization of the bone fracture gap, regulating the interfragmentary movement.

The role of the mechanical stabilization on the design of fracture fixators has evolved very much in the last years, updating from the concept of "open reduction and internal fixation (ORIF)" to "biological fixation" (Perren, 2002). In both cases, differences are presented from a biological and mechanical point of view. In fact, the concept of "biological fixation" is based on the application of the fixator as a minimally invasive percutaneous osteosynthesis (MIPO). So, the contact of the implant with bone is reduced at maximum, avoiding the damage to the blood supply. In addition to biological differences, there is also a different concept in the role of the mechanical stabilization. In the "biological fixation" primary ossification is avoided, promoting the occurrence of a secondary

*Corresponding author. Tel.: +34 976 76 27 96; fax: +34 976 76 26 70.
E-mail address: jmgaraz@unizar.es (J.M. García-Aznar).

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ossification mechanism that induces the formation of bone callus (Manjubala et al., 2009; Vetter et al., 2010). Therefore, the mechanical design concept is updated from an absolute stability to a controlled mechanical instability that favors the formation of bone callus. Hence, the mechanical stabilization due to the stiffness of the fixator has acquired a relevant role for achieving a successful bone healing (Bishop et al., 2003; Chao et al., 1989; Draper et al., 1997; Goodship et al., 1993; Richardson et al., 1994; Wehner et al., 2011). Many studies have examined the role of different local mechanical conditions on bone fracture healing: the influence of the magnitude of interfragmentary movement (IFM) and the initial size of the fracture gap (Claes et al., 1997; Gómez-Benito et al., 2011; Goodship and Kenwright, 1985), the stiffness of the fixation (Schell et al., 2005) and the type of movement of the gap (Augat et al., 2003; Bishop et al., 2006).

Computational models of the fracture healing process may prove useful in the determination of optimal mechanical treatments. In fact, several mechano-biological models based on finite element simulations studied the influence of local mechanical conditions on biological events that regulate the temporal and spatial evolution of the different ossification mechanisms that occur during healing (Andreykiv et al., 2008; Checa and Prendergast, 2009; Isaksson et al., 2008, 2009a; Lacroix and Prendergast, 2002b; Loboa et al., 2001; Reina-Romo et al., 2011; Shefelbine et al., 2005; Simon et al., 2011; Wehner et al., 2010). Most of these models have focused on how different mechanical stimuli (such as: fluid flow, octahedral shear strain, deviatoric strain, strain energy density, etc.) are able to predict spatial pattern distribution of tissues regulated by intramembranous and endochondral ossification (Checa and Prendergast, 2009; Lacroix and Prendergast, 2002a; Wehner et al., 2010). Other models have combined tissue differentiation rules with callus growth (Comiskey et al., 2013; García-Aznar et al., 2007; Gómez-Benito et al., 2005) or callus resorption (Ament and Hofer, 2000; Byrne et al., 2011; Isaksson et al., 2009b; Lacroix and Prendergast, 2002b) depending on the temporal stage of bone healing that they studied.

Although these mathematical models are very useful to understand the fundamental cellular mechanisms that locally regulate tissue differentiation and callus growth/resorption, they are not really helpful for the simulation of realistic bone fractures, where a whole-organ analysis is required. In fact, these models have only analyzed simple tranversal or obliques (Comiskey et al., 2013; Loboa et al., 2001) bone fractures with two fragments. However, fractures are much more complexes with very different shapes of the fracture line, complicated anatomical locations and a different number of fragments.

Therefore, the main aim of the present study is to propose a phenomenological computational model able to simulate the temporal recovery of mechanical properties of the fracture zone during the healing process, which is regulated by the mechanical stability. If this approach proves feasible, it offers the possibility of using computer simulations in the clinical treatment of complex fractures with multiple fragments, complicated geometries and different anatomical locations and in other orthopedic applications where bone regeneration occurs.

2. Material and methods

The bone fracture gap was modeled through the incorporation of interface elements that connected the two fracture ends simulating the discontinuity in the displacement field between fragments. A mathematical model is here proposed to simulate the temporal evolution of the separation between both fragments, regulated by the mechanical conditions existent in the fracture gap.

2.1. *Fracture gap/interface mechanical behavior*

To model the fracture gap behavior, 6-nodes and 8-nodes cohesive elements (Fig. 1) are used to connect the fracture ends (García-Aznar et al., 2009). The thickness of these elements, which is the dimension of the gap fracture, is thin enough to consider it negligible with respect to the overall dimensions of the bone fracture.

Accordingly, the behavior of these elements is directly established in terms of one traction versus one separation law.

The nominal traction stress vector, **t**, consists of three components: t_n, t_s, t_t, which represents the normal (t_n) (along

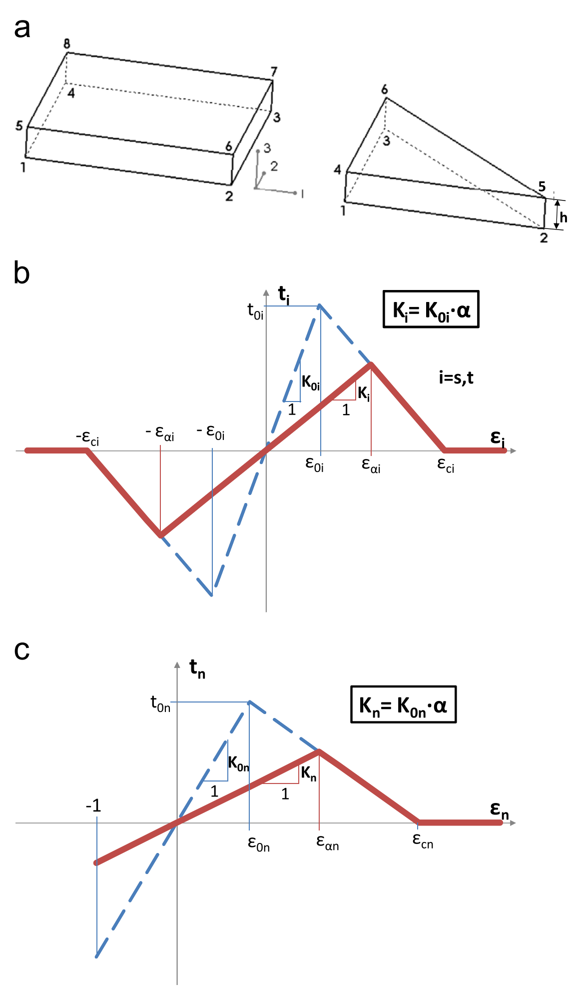

Fig. 1 – Constitutive model: (a) cohesive elements, (b) shear traction and (c) normal traction.