Callus remodelling model

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Abstract

The objective of this paper is to investigate the healing process of the callus using bone remodelling approach. A new mathematical model of bone remodelling is proposed including underload and overload resorption, equilibrium and bone growth states. The created model is used to predict the stress-stimulated change in callus density. The permanent and intermittent loading programs are considered. The analyses indicate that obtaining a sufficiently high values of callus modulus is possible only using time-varying load parameters. The model predictions also show that intermittent loading program causes delayed callus healing. The analyses are extended of the cases in which residual stress is present. The investigated bone remodelling model is suitable for more complex finite element calculations with real bone geometry. Understanding how mechanical conditions influence callus remodelling process may be relevant in the bone fracture treatment and initial bone loading during rehabilitation.

Keywords: callus, bone remodelling, mechanical stimulus, bone healing

1. Introduction

Bone tissue is capable to quickly regenerate its original structure and functionality when a fracture occurs. After trauma bone's natural response is to form a callus tissue between fractured parts. According to Wolff's law, a bone has the ability to change its material properties (e.g. density) and external architecture to adapt to applied loads via a biological process called remodelling. The callus tissue plays the key role during healing as it binds two bone parts in the process of mineralization in which bone density increases (mechanical properties of callus change). Although several studies have used computer modelling techniques to investigate bone healing process, to date the complete, mathematical description of remodelling has not been proposed. The current models of the bone remodelling are often used to model changes in bone density around implant, dental the most. Among them a few consider bone resorption due to overload which may lead to delayed healing or bone non-union. Moreover, there are no such studies in relation to the callus, which is also a bone tissue. Therefore, the aim of this study is to propose a mathematical model including both underload and overload resorption and to investigate the effect of permanent and intermittent load programs on callus density change in time.

2. Model and method

The proposed model takes into account four possible states of bone remodelling: underload resorption, the equilibrium state called 'lazy zone', the bone growth (callus density increase) and overload resorption. The elastic stain energy density (SED) is selected in this approach to define mechanical stimulus due to being employed in a number of bone remodelling studies [4,6,7]. Based on the Huiskes theory [1] and Lin [5] paper a new bone remodelling model has been proposed:

$$\frac{\mathrm{d}\rho}{\mathrm{d}t}=\begin{cases}B(\psi-K_{\mathrm{min}}), & \psi<K_{\mathrm{min}}\\ 0, & K_{\mathrm{min}}\le\psi\le K_{\mathrm{max}}\\ D(\psi-K_{\mathrm{over}})^2+K_{\mathrm{w}}, & \psi>K_{\mathrm{max}}\end{cases}\qquad(1)$$

where parameter ψ $[J/g]$ is chosen as a remodelling stimulus which denotes strain energy density SED $[J/cm^3]$ per bone mass density ρ $[g/cm^3]$, B and D are remodelling constants and K_{min}, K_{max}, K_{over}, K_{d}, are the stimulus threshold values (Fig.1). A bone tissue resorbs when the mechanical stimulus drops below a lower threshold value whereas bone apposition (growth) occurs when the load exceeds an upper threshold value. If the mechanical stimulus remains between the threshold values (lazy zone) remodelling does not occur. Moreover, when the mechanical stimulus increases excessively, overload resorption may occur causing bone loss.

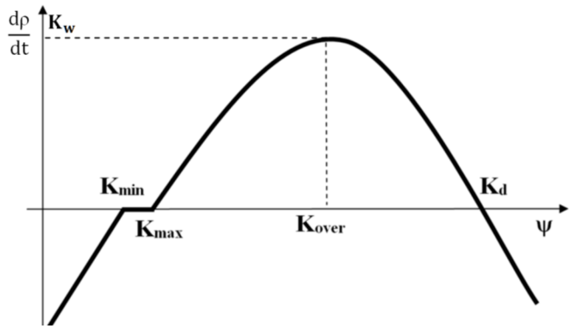

Figure 1: Bone density rate in relation to mechanical stimulus ψ

It is noted that there are different relations between density and bone Young's modulus E available in the literature. In this work, following equation is adopted:

$$E=c\rho^3\qquad(2)$$

where c is a constant [3]. The ordinary differential Eqn. (1) is integrated numerically by using the forward-Euler method:

$$\rho(t+\Delta t)=\rho(t)+\frac{\mathrm{d}\rho}{\mathrm{d}t}\Big|_t\cdot\Delta t\qquad(3)$$

Using Eqn. (3) the change in bone density at each time step is calculated. Then the corresponding elastic modulus is updated according to Eqn. (2). The next step of calculation is then performed using modified material properties. The iterative process continues until a 200 [MPa] Young's modulus is achieved. According to Knets [2] such a value indicates a bone union. This investigation focuses on the bone growth when callus is subjected to load. Hence, the analysis is mainly addressed to the interval $K_{\max} \leq \psi \leq K_{\mathrm{d}}$. Rectangular cross-section $(b \times h)$ is chosen for studying the model's properties. The analysis is carried out for a section loaded with permanent values of bending moment M and shear force T. These enforce heterogonous state of stress which results in unavoidable material inhomogeneity. A complex stress state implies that the value of strain energy density varies along the height of the section $-h/2 \leq z \leq h/2$.

3. Results

3.1 Permanent loading program

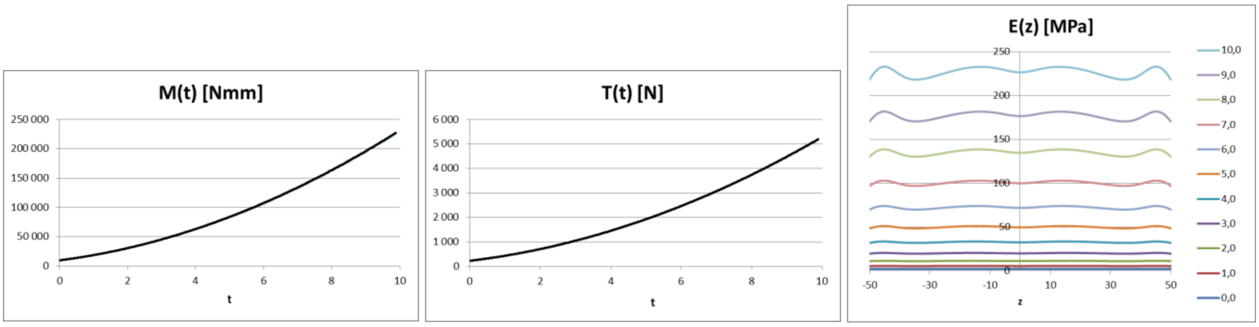

Figure 2. The Young modulus z-distribution in time using permanent loading program

3.2 Intermittent loading program

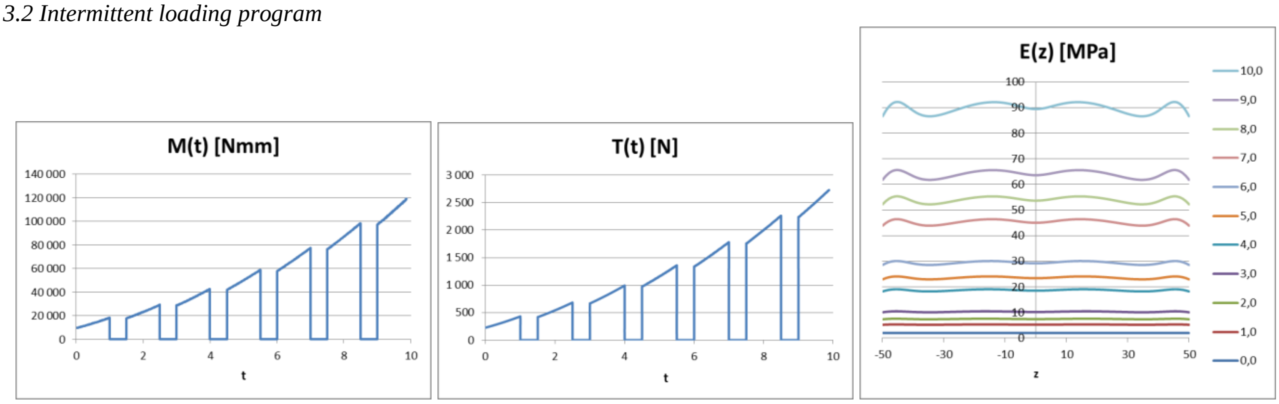

Figure 3. The Young modulus z-distribution in time using intermittent loading program

4. Conclusions

The proposed model allows to predict the density (and elasticity modulus) of callus tissue in time, depending on the applied loading program. It also provides the ability to control the load in order to obtain optimal (close to homogeneous) density distribution in the callus tissue. The analyses indicate that obtaining sufficiently high values of callus modulus is possible only using time-varying load parameters. The model predictions also show that intermittent loading program causes delayed callus healing.

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