THE DAMAGE MECHANICSAPPROACH OF BONE CONSIDERING THE MECHANICAL-ELECTRICMAGNETIC COUPLING EFFECTS

Yu Shouwen[1,], Qu Chuanyong[1,2,],Feng Xiqiao [1,]
[1] *Tsinghua University, Beijing,100084,China*
[2] *Tianjin University,300072,China*

The damage behavior of bone tissues has attracted many interests of those scientists and engineers due to their load bearing function. The coupling and healing effects of mechanical, electrical, and magnetic fields are integrated into the new damage evolution model. Several illustrative simulations are presented to validate the proposed theoretical model. The influence of those mechanical and non-mechanical factors on the bone damage and healing are simulated based on the new damage model. Those factors include mechanical overload, electromagnetic field, mechanical disuse, estrogen deficiency and bisphosphonate.

BONE DAMAGE MODEL AND EVOLUSION LAW

Bone is a rigid tissue which is subjected to complicated and varying mechanical loadings during its whole life. Fortunately, bone has an amazing self-repairing property to enable it operate under certain conditions of stresses and strains that are sufficiently high to cause damage. The presence of cracks and other types of damage existed in its micro-structure, and deliberately replaces damaged regions with new material by remodeling. Therefore, a certain amount of microdamage is not only a negative aspect for bone as a supporting material but, sometimes, a positive aspect to strengthen and also renew the bone . In this paper, an attempt is made to establish such a model for the damage/repair process of bone based on the concepts of continuum damage mechanics and the understanding of the biophysical mechanisms of bone remodeling and healing. The main concepts and the evolution equations of the bone damage model will be described. The adaptation of the internal structure of bone is formulated in terms of bone porosity and damage level, and the bone tissue modeled as a structural material is characterized by several internal variables. First, an internal scalar variable is defined to rationalize the macroscopic degradation of mechanical properties induced by the microscopic structural damage, as in continuum damage mechanics. The following damage factor is used to quantify the magnitude of bone damage in authors paper [1,2]

$$D = 1 - \frac{E}{E_0} \tag{1}$$

$$\frac{\mathrm{d}D}{\mathrm{d}t} = \frac{\mathrm{d}D_f}{\mathrm{d}t} - \frac{\mathrm{d}D_h}{\mathrm{d}t}, \qquad \frac{\mathrm{d}D_f}{\mathrm{d}t} = k\varepsilon^{q_1} R_L \tag{2}$$

The remodeling task is achieved by the so-called basic multicellular units (BMUs) composed of tissue-resorbing osteoclasts and tissue-forming osteoblasts, which work in a coupled manner. Here the number of the BMUs resorbing the damaged tissue is expressed by [2]

$$N_R = N_{R(\max)} \left[1 - \exp\left(\frac{k_r D_s}{1 - D_s} \right) \right] \tag{3}$$

Then the number of the refilling BMUs is written as

$$N_F = k_f N_R \tag{4}$$

where the coefficient k_f correlates the refilling and the resorbing processes. In this study, k_f is taken in the form of a piecewise function:

$$k_f = \begin{cases} c_0 & \Phi_L \le \Phi \le \Phi_U \\ c_0 + (c_{\max} - c_0)\left[1 - e^{k_s(\Phi - \Phi_U)}\right] & \Phi > \Phi_U \end{cases} \tag{5}$$

Based on above equations, two important cases such as (1) mechanical disuse, and (2) estrogen deficiency and bisphosphonate are considered and the corresponding damage evolution law are described respectively. The parameter Φ stands for the intensity of the environmental stimulus and is expressed as

$$\Phi = C_{ij}\varepsilon^{q_2} R_L + \left(C_i E_i + G_i H_i\right) f_e \tag{6}$$

where C_{ij}, C_i and G_i are the damage rate coefficients, ε, E_i and H_i are the intensities of the applied strain, electrical field and magnetic field, respectively. It is reasonable to assume that the damage healing rate is proportional to the number of BMUs that participate in the refill process:

$$\frac{\mathrm{d}D_h}{\mathrm{d}t} = k_h N_F \qquad \frac{\mathrm{d}p}{\mathrm{d}t} = Q_R N_R - Q_F N_F \tag{7}$$

Therefore, the porosity, p , is another internal variable to describe the relative change of mass density of bone. The elastic modulus is approximately related to the porosity by [1,2]

$$\begin{aligned} E_0 = {} & (8.83\times10^5)p^6 - (2.99\times10^6)p^5 + (3.99\times10^6)p^4 - (2.64\times10^6)p^3 \\ & + (9.08\times10^5)p^2 - (1.68\times10^5)p + 2.37\times10^4 \end{aligned} \tag{8}$$

Combined equations (1) to (8),The bone damage and remodeling with the effects of mechanical, electrical, and magnetic field loadings can be described by the following evolutionary equations of the damage factor D and the porosity p:

$$\begin{cases} \dot{D} = \Im\left[\text{☎}(\varepsilon, E_i, H_i), D, p\right] \\ \dot{p} = \Re\left[\text{☎}(\varepsilon, E_i, H_i), D, p\right] \end{cases} \tag{9}$$

We know from the that reconstruction of bone and bone injury are closely linked, electromagnetic stimulation has stimulation effect on reconstruction of bone, what is the influence of electromagnetic field on bone injury? It the influence positive or negative? How shall we utilize the influence to improve the quality of rehabilitation process of osteoporosis? Those are problems that need to be solved and can be described by evolution laws (9) .Some crucial physical and biological mechanisms underlying the sophisticated damage, remodeling and healing process of bone tissues have been incorporated in the model. Especially, an evolutionary law of bone damage and the corresponding modeling methodology are presented to analyze the complicated damage/repair behavior of bone under multi-fields. Then the numerical examples are considered to verify the present theoretical model in damage mechanics framwork and the influence of those mechanical and non-mechanical factors on the bone damage and healing are simulated based on the new damage model. Those factors include (1) mechanical overload, (2) electromagnetic field, (3) mechanical disuse, (4) estrogen deficiency and bisphosphonate. The results can be shown in several figures. Then the detailed influences of coupling effect on those factors are discussed.

References

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