Bioactive Materials 1 (2016) 77–84

Contents lists available at ScienceDirect

Bioactive Materials

journal homepage: http://www.keaipublishing.com/en/journals/bioactive-materials/

# Effects of external stress on biodegradable orthopedic materials: A review

Xuan Li [a, b], Chenglin Chu [a, b, *], Paul K. Chu [c]

[a] School of Materials Science and Engineering, Southeast University, Nanjing, 211189, China
[b] Jiangsu Key Laboratory for Advanced Metallic Materials, Southeast University, Nanjing, 211189, China
[c] Department of Physics and Materials Science, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong, China

ARTICLE INFO

*Article history:*
Received 17 February 2016
Received in revised form
2 September 2016
Accepted 4 September 2016
Available online 13 September 2016

*Keywords:*
Biodegradable orthopedic materials
External stress
Stress mode
Degradation rate
Mechanochemistry

ABSTRACT

Biodegradable orthopedic materials (BOMs) are used in rehabilitation and reconstruction of fractured tissues. The response of BOMs to the combined action of physiological stress and corrosion is an important issue *in vivo* since stress-assisted degradation and cracking are common. Although the degradation behavior and kinetics of BOMs have been investigated under static conditions, stress effects can be very serious and even fatal in the dynamic physiological environment. Since stress is unavoidable in biomedical applications of BOMs, recent work has focused on the evaluation and prediction of the properties of BOMs under stress in corrosive media. This article reviews recent progress in this important area focusing on biodegradable metals, polymers, and ceramics.


**Contents**



* Corresponding author.School of Materials Science and Engineering, Southeast University, Nanjing, 211189, China.
*E-mail address:* clchu@seu.edu.cn (C. Chu).
Peer review under responsibility of KeAi Communications Co., Ltd.

http://dx.doi.org/10.1016/j.bioactmat.2016.09.002

## 1. Introduction

Orthopedic biomaterials are commonly used in rehabilitation and reconstructing the mobility of millions of patients [1,2] and recently, biodegradable materials have attracted much interest in orthopedics due to their degradability [3–5]. Biodegradable orthopedic materials (BOMs) include metals such as magnesium (Mg) alloys [6], polymers [7], ceramics [8], and composites. The mechanical properties of bone fixation implants must be adequate and match those of bone or tissues, otherwise early implant failure, secondary fracture, and other deleterious effects such as inflammation may occur.

Although the properties of BOMs is generally related to the microstructure and alloying elements [6,9–15], the external physiological environment, especially stress and corrosive media, affects the behaviors as well. *In vitro* and clinical investigations have revealed the combined effects of stress and corrosion in early implant failure [16–19]. For example, nearly 90% of the surface fracture on Ti-6Al-4V cementless hip prosthesis is caused by the combined effects of dynamic cyclic stress and corrosive media [20]. Tissue healing is sensitive to the implant properties which can be altered by the external environment and so it is important to study and understand the performance of BOMs under stress and in a corrosive medium. In this paper, recent progress in this area is reviewed in order to provide insights into the role of external stress in the degradation of BOMs and design of new orthopedic biomaterials.

## 2. Physiological stress

In order to understand the influence of external stress on BOMs, the physiological load modes are first described. Physiological stress *in vivo* varies with the activities, bone dimensions, and locations [21–24] and multiple types of load may affect the activity [25–28]. Table 1 shows the physiological load modes and magnitude for different activities. During normal walking, the peak axial compression force at the femur is about 1.12 body weight (BW) and the maximum bending moment is about 5 BW·cm [25]. Different walking speeds lead to different peak values. For example, the peak axial force when jogging is about 1.29 times that of normal walking [26]. The strain of bones under different activities is about $400 \times 10^{-6}$ ~ $2000 \times 10^{-6}$ [22], suggesting the stress would be 0.8 Mpa–40 MPa for bones (considering the elastic modulus of the bone is 20 GPa). Furthermore, the load modes are different for different activities and bone types [27,28]. Loadings are dynamic and the frequencies are different. For example, the frequency is 1–3 Hz during normal walking and goes up to 9–20 Hz during running [29].

The effects of physiological stress on bone formations have been studied [30–33]. Generally, it is believed that dynamic stress can promote the formation and growth of bones, whereas static stress does not impose such effects. In fact, the study by Robling et al. [34] suggests that static loads suppress normal bone growth and the effects are different from those arising from dynamic stress. In another study [35], loads are applied on a porous coated implant based on the turkey ulna model and the effects of different dynamic loads on the bone ingrowth are studied. The results reveal that principal tensile or compressive strain is more important to bone adaptation, whereas shear strain has little effects. In this respect, dynamic compression, tension, and bending benefit bone healing. Thus, the behaviors of the implant materials under the stress condition, especially the dynamic stress condition, are significant for the implants.

## 3. Response of biodegradable metals to external stress

Biodegradable metals especially Mg alloys are considered next-generation metallic biomaterials [36]. As orthopedic biomaterials, Mg alloys have the following advantages [4,37,38]:

**Table 1**
Physiological load mode and magnitude of bones for different activities.

| Authors | Bones | Activities | Peak values of loads | |
|---|---|---|---|---|
| Duda et al. [25] | Femur | Walking | Axial force: ~1.12 BW<br>Bending moment: ~5 BW·cm | |
| Taylor et al. [26] | Femur | Jogging<br>Stair descending<br>Walking<br>Treadmill walking<br>Stair ascending | Axial force: ~3.6 BW<br>Axial force: ~3.1 BW<br>Axial force: ~2.8 BW<br>Axial force: ~2.75 BW<br>Axial force:~2.8 BW | Bending moment:<br>8.5–9.8 BW·cm (antero-posterior axis)<br>4.7–7.6 BW·cm (medio-lateral axis)<br>Axial torque: 0.2–1.3 BW·cm |
| Taylor et al. [27] | Femur | Walking (0.99–1.51 m/s) | Axial force:~2.5 BW<br>Shear force: 0.4–0.54 BW<br>Axial torque:7 N m | |
| | | Ascending stairs | Axial Force: ~2.5 BW<br>Axial torque:6.2 N m | |
| | | Descending stairs | Axial Force: ~2.81 BW<br>Axial torque:7.3 N m | |
| | | Rising from the chair | Axial Force: 2.09 BW<br>Axial torque:7.9 N m | |
| Wehner et al. [28] | Tibia | Gait | Axial force: ~4.7 BW<br>Bending moment in the sagittal plane: ~7.16 BW·cm | |
| Gruber et al. [29] | Tibia | Rearfoot running<br>Forefoot running | Impact shocking frequency: 9–20 Hz<br>Impact shocking frequency: 3–8 Hz | |