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Sensitivities of biomechanical assessment methods for fracture healing of long bones

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ABSTRACT

There is a controversy as to whether the biomechanical methods are feasible to assess fracture healing of long bones. This paper investigated the sensitivities of two biomechanical methods, torsion and bending, for assessing fracture healing of long bones; both a simplified beam model and finite element model of an artificial femur were employed. The results demonstrated that, in the initial healing stage, the whole-bone stiffness of the fractured bone is extremely sensitive to the variation of the callus stiffness at the fracture site; when the shear (or Young's) modulus of the callus reaches 15% that of the intact bone, the whole-bone stiffness rises up to 90% that of the intact bone. After that, the whole-bone torsional (or bending) stiffness increases slowly; it becomes less sensitive to the variation of the callus stiffness. These results imply that the whole-bone stiffness is of limited reliability to assess the healing quality particular at late stages of the healing process. The simplified model in this paper provided a theoretical framework to explain why the whole-bone stiffness is insensitive to the healing process of fractured long bones in the late stage of healing. The conclusions obtained from the simplified model were verified with the finite element simulations of the artificial femur.

1. Introduction

Assessment of healing progress of fractured bones is important both in orthopedic practice and research which evaluates outcomes of certain treatments, drugs, or rehabilitation regimes. The healing status of fractured long bones is clinically assessed by radiological and manual methods, which have been proved subjective and inaccurate in determining whether a fracture has healed [1–5]. The assessment of the healing process basically is to monitor the material strength at the fracture site [6,7]. As measuring the ultimate strength involves destructive test, which is not applicable in clinical practice, non-invasive monitoring techniques, such as measurement of bending or torsional stiffness and resonant frequencies, have been proposed for quantitative assessment of callus material properties [8–19]. However, whether the bending and torsional stiffness can define the degree of fracture healing is questionable [20–24] as the relationship between the stiffness of the whole bone and the callus strength at the fracture site still remains unknown.

There are two problems in using the whole-bone stiffness as a measure of the healing process. The whole-bone stiffness rises rapidly in the early stage of bone healing [13] and consequentially it does not change much in the late healing stage [7,22]. It has been shown experimentally that the whole-bone stiffness increases at approximately double the rate of the ultimate bending strength [25], therefore, when the whole-bone stiffness of the fractured bone has approached that of the intact bone, the strength of the fractured bone will only be a half of that of the intact bones. Chehade et al. [7] observed that the bending stiffness can be used to predict strength only in the early stages of healing; once the callus reaches a level of stiffness equivalent to 65% of the intact bone there is no longer a correlation between stiffness and strength. Roberts and Steele [22], using a rod model, demonstrated that the increases in the bending stiffness are small in the late stage of fracture healing; their results suggested that the whole-bone stiffness must be used prudently beyond the initial healing stage. Clinical and experimental studies have also shown that the whole-bone stiffness is not reliable to assess the degree of fracture healing. Even though the external fixator was removed according to the suggested threshold value for the bending stiffness of a healing human tibia (i.e., 15 Nm/degree in the sagittal plane [10]), Wade et al. [11] found some tibial fractures proceeded to a mal-union.

The controversy on the reliability of the whole-bone stiffness to assess the healing status is partly due to the lack of a theoretical analysis, which relates the whole-bone stiffness to the healing degree at the fracture site. The relation between the whole-bone stiffness of the fractured bone and the callus stiffness at the fracture site has never been theoretically investigated and some researchers

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mistakenly treated the measured whole-bone stiffness as the indicator of the callus stiffness at the fracture site. Due to the varying opinions in the literature, this study aims to investigate the sensitivities of torsional stiffness and bending stiffness of long bones to the healing process, i.e., their variations versus the callus stiffness at the fracture site. Both the simplified beam model and the finite element (FE) model of an artificial femur were employed; three fracture gap sizes, 4, 8, and 16 mm, were simulated. The simple model theoretically reveals the relation between the whole-bone stiffness of the fractured bone and the callus stiffness; the finite element analyses verify the conclusions obtained from the simple model.

2. Methods

A fractured human femur was modeled by an Euler beam and Castigliano's theorem was used to obtain the effective stiffness of the whole bone; the relation of the whole-bone stiffness with the callus stiffness at the fracture site was established. Furthermore, the finite element model of the fractured femur was developed for the purpose of verification.

2.1. Analysis of a simple model

A fractured femur was represented by a cylinder with a length of L [22,26,27] as illustrated in Fig. 1(a–d) A callus was shaped by an arc with the origin at the center of the fracture gap. It intercepted the periosteal surface at the distance of t from the bone fragment ends. The radius of the arc was $\sqrt{[R^2+(g+t)^2]}$ with $2g$ and R being the gap size and radius of the periosteal surface. The radius (y_c) of a cross section at the position z was decided by the relation: $y_c^2+(z-s)^2=R^2+(g+t)^2$, where s represented the location of the fracture gap. The cross section at the position Z consisted of two areas: $A_B=\pi(R^2-r^2)$ and $A_C=\pi({y_c}^2-R^2)$, which represented the original bone section and the additional section induced by the callus. The moments of these two areas were $I_B=\frac{\pi(R^4-r^4)}{4}$ and $I_C=\frac{\pi(y_c^4-R^4)}{4}$; their polar moments were $J_B=2I_B$ and $J_C=2I_C$.

The Young's moduli of the intact bone and the callus were denoted by E_B and E_C. Hence the flexible rigidity, $E(z)\,I(z)$, was equal to $E_C\cdot I_B+E_C\cdot I_C$ for $|z-s|\le g$ (i.e., the fracture gap) and $E_B\cdot I_B+E_C\cdot I_C$ for $g<|z-s|\le(g+t)$ (i.e., the bone part with the callus above it). Similarly the shear modulus of the intact bone and callus part were G_B and G_C; the torsional rigidity, $G(z)\cdot J(z)$, was equal to $G_C\cdot J_B+G_C\cdot J_C$ for $|z-s|\le g$ (i.e., the fracture gap) and $G_B\cdot J_B+G_C\cdot J_C$ for $g<|z-s|\le(g+t)$ (i.e., the bone part with the callus above it).

Considered the case that the beam was under pure torsion with a torque T being applied at both ends, the strain energy stored in the beam [28] was expressed as:

$$U=\int_0^L\frac{T^2}{2G(z)\cdot J(z)}dz \tag{1}$$

By using Castigliano's theorem [28], the angle of rotation, ϑ ($=\delta U/\delta T$), was obtained:

$$\vartheta=2T\int_0^L\frac{1}{2G(z)\cdot J(z)}dz \tag{2}$$

The torsional stiffness of the whole bone ($K=T/\vartheta$) was expressed as:

$$K=\frac{1}{\int_0^L\frac{1}{G(z)\cdot J(z)}dz} \tag{3}$$

The stiffness for the corresponding intact bone was obtained by taking $G(z)\cdot J(z)$ as a constant ($G_B\cdot J_B$), i.e., $\tilde{K}=G_BJ_B/L$. Thus the dimensionless stiffness of the fractured bone for torsion was defined as:

$$\bar{K}=K/\tilde{K}=\frac{1}{\frac{G_B\cdot J_B}{L}\int_0^L\frac{1}{G(z)\cdot J(z)}dz} \tag{4}$$

Similarly, the dimensionless stiffness of the whole bone for 4-point bending was expressed as:

$$\bar{K}=K/\tilde{K}=\frac{\frac{(s-a)^2(s+2a)}{3E_BI_B}}{2\left[\int_0^{s-a}\frac{z^2}{E(z)\cdot I(z)}dz+\int_{s-a}^{s}\frac{(s-a)^2}{E(z)\cdot I(z)}dz\right]} \tag{5}$$

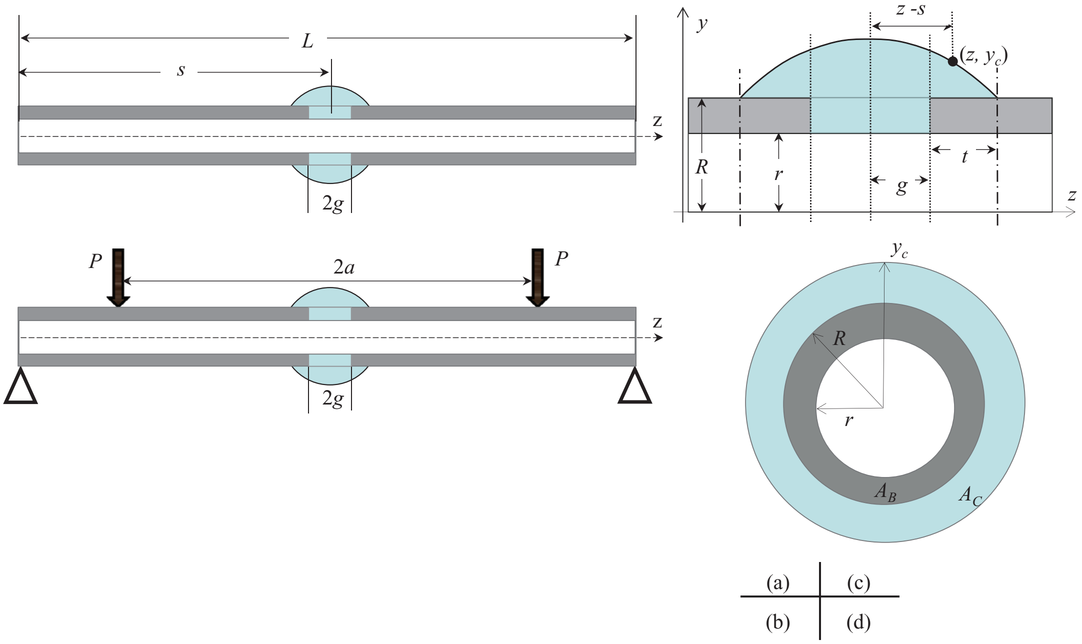

Fig. 1. (a–d). Modeling a long bone with a transverse fracture as a beam. The callus zone has different material properties from that of the rest of the bone. (a) For torsion: a torque is applied at both ends. (b) For 4-point bending: the beam is simply supported at both ends and subjected to two equal forces P. (c) The geometry of the fracture site. (d) A cross-section at the fracture site.

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