THE ROLE OF IN-PHASE AND OUT-OF-PHASE TORSIONAL LOADING ON CORTICAL BONE FATIGUE

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Introduction

During daily activities human bones are subjected to multiaxial cyclic loading (1-3) and it has been recently demonstrated that superposition of torsional on axial loading leads to a ten-fold reduction in the fatigue life of bone (3). However, little is known about how the relationship between axial and torsional loadings affects the fatigue life of bone. Evidence from engineering literature suggests that the alterations in multiaxial loading regime including the phase angle between the axial and torsional loading has a dramatic effect on the fatigue behavior of materials (4-5). Furthermore, there is considerable evidence in the biomechanics literature that multiaxial loading of long bones is subjected to alteration with the speed of walking (1), strenuous activities (4-5). Furthermore, there is considerable evidence in the biomechanics literature that multiaxial loading of long bones is subjected to alteration with the speed of walking (1), strenuous activities (4-5).

Methods

Twenty cylindrical dumbbell specimens with reduced gage section of 3 mm diameter were wet machined from bovine femurs. Ten of these specimens were subjected to torsional loading (±30% UTS) applied in phase with axial loading (±50% UTS) at 2 Hz on a MTS MiniBionix II, under constant irrigation of saline. Under this scheme, the peaks of the axial and torsional loadings coincide and produce principal stresses (Max. $\sigma = 87$ MPa; Max. $\tau = 47$ MPa) at two fixed planes oriented at ±7 degrees with respect to the specimen axis. The remaining ten specimens were subjected to torsional loading (±30% UTS) applied 90 degrees out-of-phase with axial loading (±50% UTS). Under this scheme, the peaks of the axial loading occur at zero torsional loading and vice versa to produce principal stresses (Max. $\sigma = 80$ MPa; Max. $\tau = 60$ MPa) at two principal planes that rotate between ±7 and ±14 degrees with respect to the specimen axis. The selection of load levels for axial and torsional loadings is based on a previous analysis of human strain gage data (2).

The loss of tensile, compressive and torsional stiffnesses were continuously monitored throughout each test to determine the damage development and fatigue behavior of bone. The number of cycles to failure (N) were measured and compared between the groups using non-parametric sign rank test. Following testing, fracture surfaces of typical specimens were sputter-coated with gold and prepared for viewing under a scanning electron microscope.

Results

An increase in phase angle from 0 to 90 degrees caused a seven-fold increase in the fatigue life of bone [N (In-phase) = 109±87; N (Out-of-phase) = 771±75; p = 0.002]. The stiffness loss profiles of both in-phase and out-of-phase load cases displayed the three classic stages of fatigue behavior but were inherently different (Figure 1). In-phase load cases displayed a similar loss of tensile, compressive and torsional stiffnesses suggesting that damage produced under in-phase loading proportionately affected all three stiffnesses (Figure 1). This observation is consistent with the occurrence of mixed-mode crack initiation and propagation and the same was clearly visible on the fracture surfaces of the specimens subjected to in-phase loading (not shown). In contrast, out-of-phase load cases displayed a much smaller contribution of mixed-mode failure (not shown) and underwent a disproportionately higher loss of stiffness in one mode only (torsion) (Figure 1). Furthermore, by comparing the cycle to failure and stiffness loss profiles it becomes immediately clear that the out-of-phase load cases displayed a more gradual loss of stiffness per loading cycle and spent more cycles in each of the three phases of fatigue.

Discussion

The increase in fatigue life of bone noted for out-of-phase load cases demonstrates that the alteration of the relationship between axial and torsional loading causes dramatic changes in the fatigue life of bone. Interrelationships between axial and torsional loadings including the phase angle is, therefore, important and should be investigated in a variety of loading situations associated with fractures.

The observed changes in fatigue behavior of bone with phase angle are a result of many factors. Firstly, phase angle influences the magnitude of mixed mode crack initiation and propagation. For example, simultaneous application of tensile and torsional loadings during the first half of in-phase loading is known to initiate and drive a crack into the surface under mode I (tensile) and mode III (out-of-plane shear) conditions. This transverse/inclined crack then proceeds vertically under longitudinal (mode II) and transverse (mode III) shear generated by simultaneous application of the compressive and torsional loadings during the second half of the in-phase load cycle (7). Secondly, damage in most bone-like materials occurs on principal planes and, out-of-phase loading causes principal planes to rotate within the specimen (see methods). The rotation of principal planes diffuses the damage throughout the specimen (rather than concentrating it on one plane), causes gradual stiffness loss (Figure 1), delays the onset of a fatal crack and increases the fatigue life. Lastly, out-of-phase loading reduces the effective principal stresses on the specimen and increase the fatigue life. The increase in fatigue life (7 times), however, is greatly disproportional to the magnitude of stress reduction (<1%) (See methods) suggesting that load reduction plays a minimal role.

References