ENDURANCE LIMIT FOR BOVINE TRABECULAR BONE

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INTRODUCTION:
Stress fractures associated with prolonged exercise and age-related fragility fractures associated with bone of compromised quality are caused by fatigue loading. Some engineering materials (e.g. steels) have a fatigue limit: i.e. there is a stress plateau in the stress-life (S-N) curve. When loaded below the stress plateau, these materials have an infinite fatigue life. Other materials do not exhibit a fatigue limit (e.g. aluminum). For these materials, the endurance limit is defined as the stress amplitude corresponding to a somewhat arbitrary large number of cycles of fatigue (e.g. various texts suggest $10^6$ to $10^8$ cycles). In our previous work on compressive fatigue of bovine trabecular bone, we hypothesized that a fatigue limit may exist at a normalized stress, $\Delta \sigma/E_o$, of approximately 0.0035. In this study, we have performed compressive fatigue tests at normalized stresses between 0.0015 and 0.01. We did not observe a threshold below which the fatigue life was infinite at these normalized stress levels. However, we did observe an endurance limit corresponding to $10^6$ cycles to failure at a normalized stress of approximately 0.0017.

MATERIALS AND METHODS:
In this study, 64 samples of bovine trabecular bone were loaded in compressive fatigue at normalized stresses, $\Delta \sigma/E_o$, of 0.0015 to 0.01. Samples of bovine trabecular bone were harvested from the proximal tibia. Waisted cylindrical specimens with a nominal diameter of 6 mm with axially aligned trabeculae were prepared using the protocol developed by Keaveney et al (1994). Specimens were kept hydrated and frozen at $-20^\circ$C at all times other than those of preparation and testing. Prior to testing, the gauge diameter of each specimen was measured five times and the mean cross-sectional area calculated. The specimen was then loaded into either an Instron 1331 or an Instron 1321 loadframe and gripped with three jaw chucks. A miniature extensometer (MTS 632.290-30, MTS Eden Prairie MN) with a 5 mm gauge length was attached to the bone using metal clips. The sample was kept moist with 0.9% saline during testing.

After mounting each specimen into the loadframe, 10 preconditioning cycles to a strain of -0.2% were applied. Data for load, strain, and position were recorded at 50 Hz. The initial modulus of the specimen was determined from the stress-strain curve of the $10^6$ cycle of the preconditioning procedure. Cyclic load values were calculated using the initial modulus and normalized stress ($\Delta \sigma/E_o$) values ranging from 0.01 to 0.0015. Specimens were loaded in compression from a nominal load of $\sim 10$ N to a maximum compressive load corresponding to the pre-determined normalized stress at a frequency of 2.0 Hz. Specimens were loaded until the elastic modulus of the sample was reduced by 10%, the specimen fractured, or runout, defined as $10^6$ cycles, was observed. A log-log plot of normalized stress versus number of cycles to failure was made and a regression of the data was performed.

RESULTS:
The stress-life data for the bovine trabecular bone tested in this study (Fig. 1) are described by the linear regression of the log-log plot ($R^2=0.91$):

$$\frac{\Delta \sigma}{E_o} = 0.0119 \left( N_f \right)^{-1.197}$$

The endurance limit corresponding to $10^6$ cycles occurs at a normalized stress of 0.0017. There is substantial scatter in the data (typically two orders of magnitude at a given stress level), so that a more conservative estimate of the normalized stress at the endurance limit is approximately 0.0015.

DISCUSSION:
At the lowest normalized stresses in this study, there was a translation of the stress-strain loops along the strain axis as a result of microdamage. At the normalized stresses used in this study, we observed no threshold below which fatigue life was infinite. However, we observed an endurance limit, corresponding to a fatigue life of $10^6$ cycles at a normalized stress of approximately 0.0017.

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