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Authors: Ahmet Çağatay Çilingir

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Design, Manufacturing and Testing of a Bone Shaft Fatigue Machine

Ahmet Cagatay Cilingir*[1]

Abstract

To determine the mechanical properties of materials subjected to repetitive loading, fatigue testing is a well–established method in engineering studies. It is believed that the cause of stress fractures in cortical bone are due to the repetitive loading. There is currently no cost–effective device that accounts for the variety of factors influencing the fatigue behaviour of bone *in vivo*. The Bone Shaft Fatigue Machine is proposed as a possible solution and designed as a rotating bending fatigue tester with a constant stress amplitude. Sheep metatarsal bone shaft specimens designed and machined for fatigue tests. The results were determined to be in accordance with the expected fatigue stresses and cycles reported in current literature. The Bone Shaft Fatigue Machine was also found to be cost-effective and applicable to the testing of materials in research areas other than the study of cortical bone.

Keywords: bone, fatigue, S-N curve

1. INTRODUCTION

Clinically observed stress fractures are thought to result from the failure of the bone after cycling loading [1], and age-related changes in cortical bone [2-4]. The fatigue life of bone is effected by its unique material properties such as viscoelasticity [5], heterogeneity [6]. The mechanical properties and fatigue life of bone also vary with loading mode [6], strain rate [5,6], stress frequency [7] and hydration level [8]. The fatigue life of bone is greater at higher stress frequencies because of its viscoelasticity. It is also shown that an increase in strain rate decreases the fatigue life of cortical bone [9, 10].

In a comparison with metals, ceramics, and polymers, bone is a largely unstandardized material. These engineering materials have specific guides for testing under environmental and loading conditions. These standards serve as a reliable, convenient resource for the creation of specimens, design of experiments, and interpretation of results. Additionally, a universally recognized standard increases the consistency and accuracy of all experiments. Since there is no better option these standards for engineering materials are roughly applied to the fatigue of bone specimens. An increase in testing

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* Corresponding Author: cilingir@sakarya.edu.tr
[1] Sakarya University, Mechanical Engineering Department, Sakarya, Turkey. ORCID: 0000-0001-7550-7883

volume and generation of results would be provided from an affordable, physiologically relevant machine. The knowledge generated from that machine could then be applied to creating standards for understanding of bone.

A physiologically acceptable fatigue machine addresses a very large audience if it is affordable. Fatigue testing machines are very expensive for academic researchers. Mechanical and fatigue tests should be applied to bone or tissue implanted into the body to evaluate the performance of the material. The purpose of the fatigue machine is to ensure testing of the fatigue of cortical bone tissue *in vivo*. A large specimen size is necessary to determine reasonable data for high cycle fatigue. The fatigue machine must be efficient, time-saving and cost–effective. Money and time are often the largest constraints associated with research, so these factors should be considered in designing of the device.

The input and technical specifications are guidelines for designing of the Bone Shaft Fatigue Machine. A physiologically relevant system is a priority for basic characteristics of the human body. However, it is too difficult or impossible to build a system exactly like the human body.

Therefore, basic features must be defined and maintained. For example, a bone sample does not need to be fatigued in human blood to maintain its natural properties. Bovine serum and phosphate buffered saline (PBS) solutions [11] provide enough hydration to maintain the appropriate mechanical properties. The mechanical properties of a sample determine its fatigue life, therefore, it is important that these properties represent the bone to determine accurate fatigue data.

2. DESIGN AND MANUFACTURING

To determine a useful fatigue data for bone tissue it is required to define a physiologically relevant testing method. The test environment [12] and loading mechanism [13] changes the behaviour of bone. Wet bone is less brittle and has a longer fatigue life compared to dry bone [8]. In a human body, cortical bone is usually loaded in tension and compression [14]. A device trying to meet these requirements provides data that may be more useful when applied to the conditions of the human body. When cortical bone is dehydrated, it demonstrates brittle fracture and the fatigue life is reduced significantly [8]. Therefore, samples should be completely immersed in the solution to prevent dehydration. Consequently, the proposed fatigue machine is required to have a PBS solution bath to keep hydration of the bone samples.

The cortical bone samples should be exposed to similar loading conditions as in human body. The bone shaft is of particular interest for fatigue testing, because this region of the body can provide the largest size and quantity for testing. The bone shaft exposed to tensile and compressive loads during daily activity [15, 16]. In order to take into account the individual loads, the fatigue machine must apply tension and compression to bone shaft. The bone shaft experiences cyclic loads of approximately 2 Hz during daily activities [17, 18]. Therefore, the fatigue machine should run at a rate of 2 Hz (120 rpm).

The predicted results from the fatigue machine should be consistent with current literature. Furthermore, location of fracture and number of cycles to failure must be consistent with those reported in other studies using a similar device.

The device must be user friendly, thus it should be simple for the user to operate for long periods of time. A graduate level engineering student should be able to learn how to fully operate the machine after a week of use. In addition, the device must not occupy much space in a laboratory and the user should be able to place samples easily. A single fatigue test may take days to perform according to magnitude and frequency of applied load, thus the device must be able to operate non-stop 24 hours.

Technical parameters relate to stress applied to the bone sample. This characteristic should be set for each test, because it is the second component required to generate S – N curves, which represent the plot of the magnitude of an altering stress versus the number of cycles to failure. A mathematical model must be determined to estimate the stress value at the predicted region of fracture. The user should be able to change the stress level. Bone samples must be tested at various stress levels to generate S – N curves.

The bone shaft fatigue testing machine is designed and manufactured to meet the defined requirements above (Figure 1). A user is capable of selecting a solution to hydrate the bone sample and also able to change applied load and frequency. Although the fatigue machine is designed for bone shaft samples, the resulting device is able to test various engineering materials.

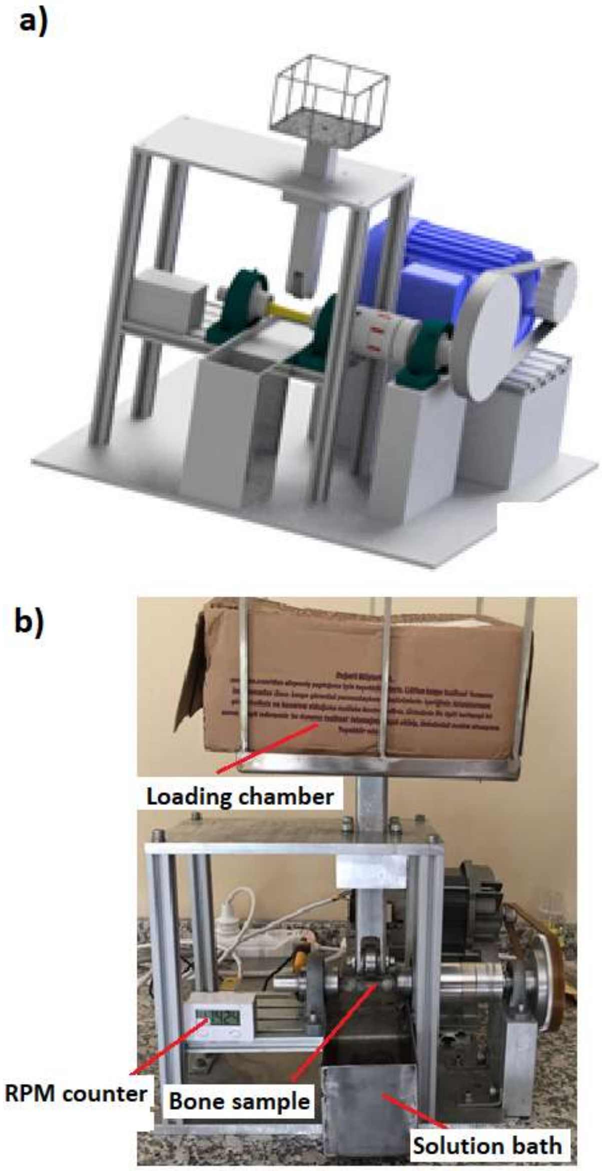

Figure 1. a) Designed and b) Manufactured Bone Shaft Fatigue Testing Machine

3. SAMPLE PREPARATION

Sheep metatarsal bones were obtained from local butcher 24 h after slaughter and, the epiphyses, or ends of the metatarsal, were removed using an electric saw. Approximately 80 mm long 10 metatarsal bone shafts were then prepared in the laboratory (Figure 2a) and frequently wet with a brush soaked in PBS during preparation. Bone shaft samples were wrapped in PBS soaked gauze and stored in a freezer at -18 °C until removed for machining; previous studies concluded that the mechanical properties of the bone were not affected by freezing [19, 20]. Before the tests, sheep metatarsal bone shaft specimens were defrost in phosphate buffered saline (PBS) solution at 4 °C for 6 hours. Bone shaft samples were fixed at the ends by using epoxy putty adhesive into the purposely designed aluminium moulds and placed in the fatigue machine as shown in Figure 2b.

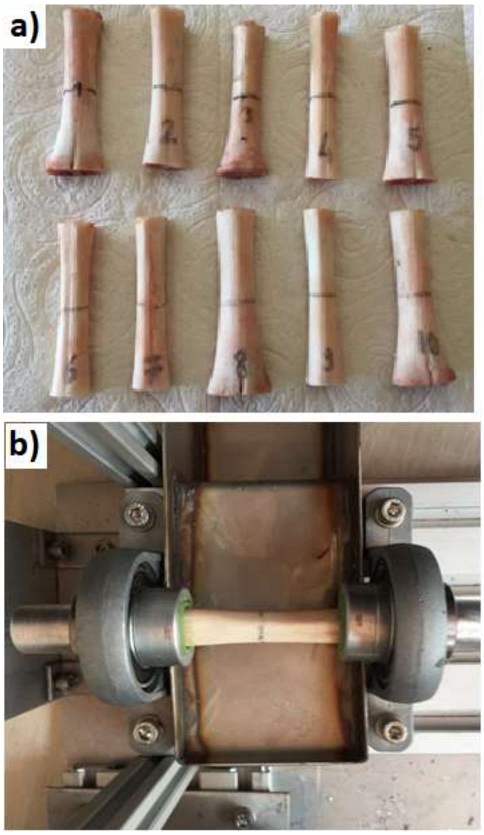

Figure 2. a) Sheep Metatarsal Bone Samples and b) Placing of Bone Sample into the Fatigue Machine

4. FATIGUE TESTS

Bone shaft samples were subjected to downward force, F (m.g), from 5 kg to 40 kg until the bone was fractured at 2 Hz (120 rpm) and the cycles to failure were read from a rpm counter on the fatigue machine. The maximum bending moment generated at the middle region of the bone shaft as shown in Figure 3a and calculated as,

$$M_e = \frac{F.L}{4} \qquad (1)$$

in which F is applied load, L is distance between the support and M_e is maximum bending moment. This region is of interest because the stress calculations are made with respect to the middle of the shaft, where fracture is expected to initiate. The sheep metatarsal bone shaft was assumed to be elliptical hollow shaft (Figure 3b), as it was acceptable assumption according to previous studies [21]. Moment of inertia for the hollow elliptical cross-section was calculated as,

$$I = \frac{\pi}{4}.[(a_1.b_1^3) - (a_2.b_2^3)] \qquad (2)$$

To calculate the maximum stress, the moment from Equation 1 and the moment of inertia from Equation 2 were put into following equation,

$$\sigma = \frac{M_e.y}{I} = \frac{M_e.b_1}{I} \qquad (3)$$

After each test, the failed bone shaft samples were measured according to Figure 3b and area moment of inertia was calculated using Equation 2. A plot of the predicted applied stress resulting from a range of applied loads (5 kg to 40 kg) was generated from Equation 3. The bone shaft holder was connected to the motor which has run at 120 rpm and a cycle counter probe was placed on bone shaft holder, thus is able to accurately read the cycle data. The number of cycles must be reported accurately because this parameter is the core of the construction of S-N curves. Bone samples were kept hydrated by using a water pump during tests (Figure 3a).

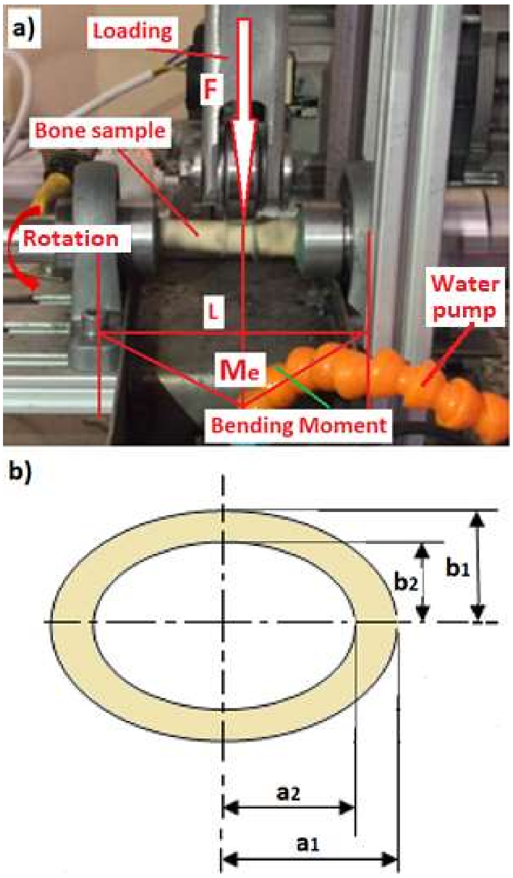

Figure 3. a) Loading conditions of the bone shaft in the fatigue machine. b) Elliptical cross-section assumption of sheep metatarsal bone shaft

5. RESULTS AND DISCUSSION

Sheep metatarsal bone shaft specimens were prepared in accordance with the specimen preparation procedure outlined in Section 3. The fatigue tests were performed in order to compare the number of cycles to failure, and fracture locations of the specimens with those reported in similar rotating bending fatigue tests of cortical bone. Ten sheep metatarsal bone shaft samples were loaded from 5 kg to 40 kg corresponding with stress levels of approximately 40 MPa to 80 MPa and tested at 2 Hz (120 rpm) in order to verify fracture was consistent with expected behaviour as reported in literature.

The first aspect to consider was the location of fracture, which was expected to occur in the middle of the bone shaft. Fracture is expected in this location because the diameter of the cross section is at a minimum so the maximum stress should be applied in that region. All samples were fractured at the middle of the bone shaft consistent with previous studies [22].

The 5 kg loaded specimen did not break for over 1.5 10^6 cycles. However the 6 kg loaded specimen was broken at almost 10^6 cycles. Therefore, 5 kg loaded specimen was declared a run-out specimen. From 6 kg to 40 kg loaded specimens fractured in 50 000 to 1 000 000 cycles (Figure 4). According to data compiled by Lafferty [7] cortical bone is expected to fatigue in the range of 10^5 and 10^6 cycles when stressed at 80 MPa and 10^7 or more cycles at 50 MPa. The fatigue test results of current study therefore indicates the presented fatigue machine is capable of fatiguing bone shaft specimens and producing results in agreement with current literature.

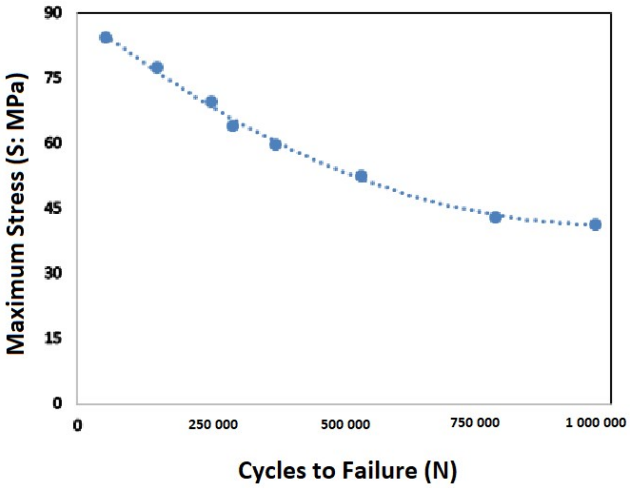

Figure 4. S-N curve of sheep metatarsal bone shaft (according to 8 bone samples)

6. CONCLUSION

The purpose of the design is essentially to quickly and inexpensively determine bone shaft fatigue lives that can be used to predict *in vivo* success more accurately than current methods. Upon completion of several tests, the Bone Shaft Fatigue Machine is a verified option for fatigue testing of bone shaft specimens and is consistent with the established purpose.

Bone shaft specimens were tested in a physiologically relevant environment. The selected PBS solution provides enough water, salt, and phosphate to preserve the mechanical properties of the bone shaft specimens. The bone shaft specimens were subjected to physiologically relevant mechanical loading. The necessary stress levels were properly applied by the device for fatigue tests. The constant stress amplitude requirement was fulfilled with the design of a weight chamber on fatigue device. The device was required to be light enough to be transported by one person. The device was also expected to be cost–effective and adaptable to a variety of testing needs. The stress level is varied by changing magnitudes of the weights on loading chamber. The variety of stress levels can then be used to generate S–N curves for materials.

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