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ACCELERATED BONE GROWTH REMOTELY INDUCED BY MAGNETIC FIELDS AND SMART MATERIALS

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INTRODUCTION

Bone Biology

Bone structure is exquisitely matched to its physical loading environment. From the cartilaginous skeletal framework formed in the embryo to the aging skeleton, bone architecture is directly related to function. Bone is a dynamic system, constantly remodeling itself by absorbing old tissue and forming new one. This capability allows bone architecture to become optimized to the loading environment. Julius Wolff first postulated that bone structure adapts to changing stress environments in 1892 [1]. Exact understanding of the process of mechanotransduction, however, has remained elusive. In addition to normal remodeling, bone growth has been shown to occur along the diaphysis, or shaft portion, of long bones such as the femur when placed in dynamic bending. Bone in this region is dense and is known as cortical bone. A bending moment placed on a long bone will cause the bone to curve creating a region of tension on one side and a region of compression on the opposing side. As the bending moment is cycled, fluid within the bone will flow from the region of compression to the region of tension creating fluid shear on cell walls within the bone which promotes the anabolic response of growth [2]. Growth from such stimuli is thought to be mediated by fluid flow around quiescent bone cells, osteocytes, and their canalicular process coursing through the bone structure [3]. Growth in this manner is directed in a latitudinal direction creating a thicker and stronger diaphysis.

The ability to accelerate bone growth has many societal benefits. Since an increase in diaphysis thickness increases bone strength, this technology could be used to help prevent bone fractures as well as hasten fracture healing. The symptoms of osteoporosis might also be diminished if a useful mechanism for bone strengthening is found. The ability to promote bone growth could also lead to better adhesion of living bone to prostheses such as hip replacements. Astronauts and pilots routinely subjected to minimum gravity environments could also benefit from mechanical loading to prevent bone atrophy.

This paper is focused on the novel use of a magnetically active composite material able to mechanically load bone samples *ex-vivo* to levels shown in the literature to accelerate growth *in-vivo* in a non-invasive, non-traumatic method. Strain values between 200με and 2000με represent physiological levels of strain on the human skeleton. Normal bone remodeling occurs in this region and ensures that bone continually renews itself. Above 2000με, the relative rate of bone formation to absorption increases and growth is observed [4]. For reference, 25000με represents pathological strain magnitude in cortical bone structure. Studies involving turkeys have shown that a 30 Hz 200με signal is sufficient to induce cortical bone growth and studies involving rats have shown that a 1050με signal is sufficient to produce cortical bone growth [5,6].

Along with strain magnitude, the strain rate, or rate at which strain is applied and released, also plays an important role in new bone formation. Based on a compilation of previous studies, Turner concluded that the strain rate and magnitude are related to the strain stimulus as shown in equation (1), where E is the strain stimulus, k is a proportionality constant, ε is the strain magnitude, and f is the strain frequency [7].

$$E = k\,\Sigma(\varepsilon\, f) \quad (1)$$

This relationship implies that a high magnitude, low frequency strain signal would produce the same anabolic response as a low magnitude high frequency strain signal.

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METHODS

Magnetostrictive Materials

Magnetostrictive materials exhibit a change in length when placed in a magnetic field. By rigidly applying this alloy in composite form to the diaphysis of a long bone and placing the bone/composite system in a cycled magnetic field, the composite will change length creating bending stress through the cross section of the bone and in turn, stimulate growth.

Terfenol-D Composite

Terfenol-D is an alloy of iron, terbium, and dysprosium. Monolithic Terfenol-D exhibits a superior large strain magnitude, but is brittle and is prone to dynamic (eddy current) losses. A composite material with enhanced functionality, resilience, and frequency bandwidth relative to those of monilithicTerfenol-D is obtained by embedding micron-sized Terfenol-D particles in an epoxy matrix magnetically aligned during the cure of the composite. A 50% volume percentage Terfenol-D composite was chosen as a balance between functional behavior and ease of manufacture. Ball-milled Terfenol-D was mixed with Derakane C-411-50 epoxy resin and cast in a 2" long, ¼" diameter aluminum cylindrical mold and baked at 70°C for 6 hours to complete the cure. The composite was subsequently machined into 1" long semi-cylinders.

Drive Coil

A coil was fabricated in order to drive the composite and create shape change. The drive coil was constructed out of 20AWG magnet wire. A spindle was machined out of steel and aluminum and was attached to a variable speed motor in order to control the layering of the wire. A thin layer of heat resistant epoxy was spread between each layer of coil to maintain structural integrity of the coil. A two-layer pick-up coil was placed inside the drive coil to measure the magnetization of the composite. The drive coil has a resistance of 18.9Ω and a field rating of 1.6kA/m/V.

Composite/Bone System

A right porcine tibia was chosen for the relatively flat surface it provides for bonding of the magnetostrictive composite. The bone ends were potted in aluminum blocks to facilitate mechanical testing using polymethylmethacrylate (PMMA). The semi-cylindrical composite was applied to the bone along the long axis of the bone with cyanoacrylate glue. Three strain gages were placed on the system. One was placed on the composite, one on the bone next to the composite, and another on the bone opposite the composite. This would allow for strain measurements on the composite and what was actually applied to the bone. Two of the strain gages are shown in Figure 1. The entire system was slid into the drive coil for testing.

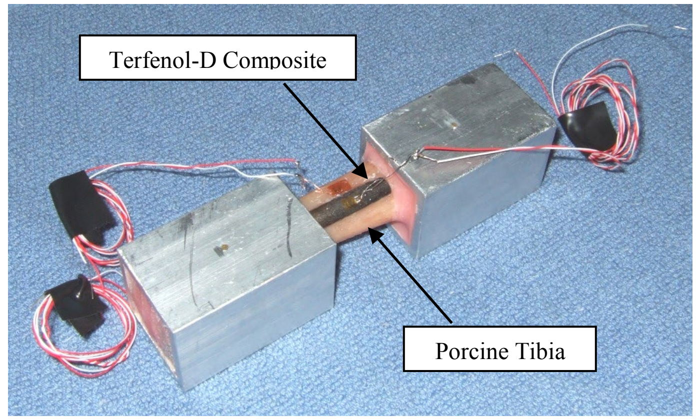

Figure 1. Composite/Bone System

RESULTS AND DISCUSSION

Prior to bonding, quasi static tests of the Terfenol-D composite were conducted at fields ranging from 110 to 170 kA/m at a frequency of 30Hz. As the field intensity is increased, the strain produced in the Terfenol-D composite increases up to a maximum of 2300με peak to peak. Increasing the field beyond 170kA/m would produce increased strain magnitude up to the saturation strain of the material but the field could not be increased beyond 170kA/m at 30Hz due to excessive heating of the drive coil.

Once bonded to the bone, strain measurements were acquired driving the composite at 30Hz and 170kA/m. The strain magnitude achieved by the Terfenol-D composite was greater than 2000με, however the bone surface was only subjected to 1000με. This loss in strain transmission was due to the viscoelastic properties of the adhesive used to bond the composite to the bone surface.

CONCLUSION AND FUTURE DIRECTION

Despite the losses across the adhesive layer, the strain level achieved on the bone surface is sufficient to promote the anabolic response of latitudinal growth in accordance with previous research. It is also noted that the strain level on both the top and bottom of the bone surface are approximately equal, implying that the bone growth would occur at the same rate around the cross section of the bone with only one application point of the composite.

Applying multiple composite semi-cylinders, instead of just one around the circumference of a long bone might lead to yet another phenomenon, longitudinal growth. Driving each composite with a single coil would cause a tension stress derived strain instead of a bending stress derived strain. This might induce the same physiological processes to occur and promote longitudinal bone growth.

In the future, a mathematical model of the adhesive layer would permit accurate prediction of applied strain for a given magnetic field and frequency. This would aid in validation of the experimental results and in developing of a control strategy for implementation of the bone growth system.

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