INTEGRATION OF A FINITE ELEMENT MODEL WITH THE DAP BONE REMODELING MODEL TO CHARACTERIZE BONE RESPONSE TO SKELETAL LOADING

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INTRODUCTION: NASA’s Digital Astronaut Project (DAP) has developed a bone remodeling model that has been validated for predicting volumetric bone mineral density (vBMD) changes of trabecular and cortical bone in the absence of mechanical loading [1]. The model was recently updated to include skeletal loading from exercise and free-living activities to maintain healthy bone using a new daily load stimulus (DLS). This new formula was developed based on an extensive review of existing DLS formulas [2], as discussed in the abstract by Pennline et al. The DLS formula incorporated into the bone remodeling model utilizes strains and stress calculated from finite element model (FEM) of the bone region of interest. The proximal femur was selected for the initial application of the DLS formula, with a specific focus on the femoral neck.

METHODS: The FEM was generated from CAD geometry of a femur using de-identified CT data [3, 4]. The femur was meshed using linear tetrahedral elements Figure (1) with higher mesh densities in the femoral neck region, which is the primary region of interest for the initial application of the DLS formula in concert with the DAP bone remodeling model. Nodal loads were applied to the femoral head and the greater trochanter and the base of the femur was held fixed. An L2 norm study was conducted to reduce the length of the femoral shaft without significantly impacting the stresses in the femoral neck. The material properties of the FEM of the proximal femur were separated between cortical and trabecular regions to work with the bone remodeling model. Determining the elements with cortical material properties in the FEM was based off of publicly available CT hip scans [4] that were segmented, cleaned, and overlaid onto the FEM.

The FEM was solved using MSC Nastran 101 linear static solution, and the output stresses were provided to the bone remodeling model to consolidate and determine a DLS outcome. The system of passing information from the FEM to the bone remodeling model was automated using Matlab. With the bone densities provided by the user, the FEM is initially read into Matlab and the initial material properties are written into the FEM file and solved using Nastran. Once complete, the output stresses are automatically read into Matlab and the DLS is calculated for a given exercise applied to the bone. As the bone density and bone volume fraction changes depending on overload or disuse, the FEM is updated with new material properties (Figure 1), which are functions of ash density and bone volume fraction, and the cycle is repeated until the duration of the simulation is complete.

CONCLUSIONS AND FUTURE WORK: A FEM was successfully integrated with the DAP bone remodeling model DLS formula to simulate the influence of mechanical stimulus on the bone remodeling process in a fully automated manner. However, there are several improvements that will be made to increase the accuracy of the FEM such as using CT data to directly map the vBMD on an elemental level and applying anisotropic material moduli instead of the current assumption of isotropic material properties. Also, the remodeling algorithm and DLS formula may be applied to each element to evaluate vBMD changes per-element resolution rather than an aggregate of the trabecular and cortical regions.

The Digital Astronaut Project (DAP) implements well-vetted computational models to predict and assess spaceflight health and performance risks, and enhance countermeasure development.

**NASA’s Digital Astronaut Project Vision Statement**

Model and Simulation Description

- The DAP has developed a bone remodeling model that has been validated for predicting volumetric bone mineral density (vBMD) changes of trabecular and cortical bone in the absence of mechanical loading [1].
- The model was recently updated to include skeletal loading from exercise and free-living activities to maintain bone using a new daily load stimulus (DLS).
- The DLS formula incorporated into the bone remodeling model utilizes strain and stress calculated from a finite element model (FEM) of the bone region of interest.
- The proximal femur was selected for the initial application of the DLS formula, with a specific focus on the femoral neck.

**Objective**

- The goal of using the FEM in concert with the bone remodeling model is to broaden the capability of the bone remodeling model to include both loading and non-loading scenarios on bone.
- The initial objective of combining the FEM with the bone remodeling model is to create a robust and fully automated simulation that helps serve as a research tool for bone.

**OBJECTIVES**

**METHODS**

- The FEM is created based on the CAD of an anonymous subject’s CT hip scan [2].
- Given the bone remodeling model is focused on the stress/strain around the femoral neck, the FEM of the CAD model is shortened in the long bone portion of the femur.
- An L2 Norm study is conducted to ensure the stresses around the femoral neck are not affected by reducing length.
- The mesh is sliced into 1 inch sections and femoral neck stress are used for comparison between iterations.

**Cortical Thickness Determination**

- The volume is meshed using Siemens Femap meshing software (Munich, Germany).
- Element sizes were reduced around the femoral neck to provide better resolution at the location where the bone remodeling model is primarily focused.
- The current approach of the FEM:
  - Linear isotropic modulus of elasticity
  - Linear tetrabahedral elements
  - NASTRAN101 linear static solution
  - Femap as the FEM pre and Post Processor

**Verification**

- Analysis of change in bone density due to normal daily walking for different body masses and steps per day.
- Results show no change in density with small decreases for minimal steps per day cases.

**Validation**

- Assumed that astronauts are likely to engage in higher daily activity that would be equivalent to 12,500 to 16,000 steps.
- Mean body weight of 725 N and walking speed of 4.0 m/s was assumed.
- The simulation results match the data reported by Lang et al [9] within the experimental standard deviation and standard error.
- Post-flight QCT data from 16 crewmembers collected at R0 and R+12 months reported in Lang et al [9].

**FUTURE WORK**

- Enhancements to the FEM:
  - Develop subject specific FEMs of the proximal femur using CT data of the subject
  - Apply the bone remodeling model to each individual element within the FEM
  - Use the CT data to directly map the stiffness for each element and include anisotropic material properties

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**REFERENCES**