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.

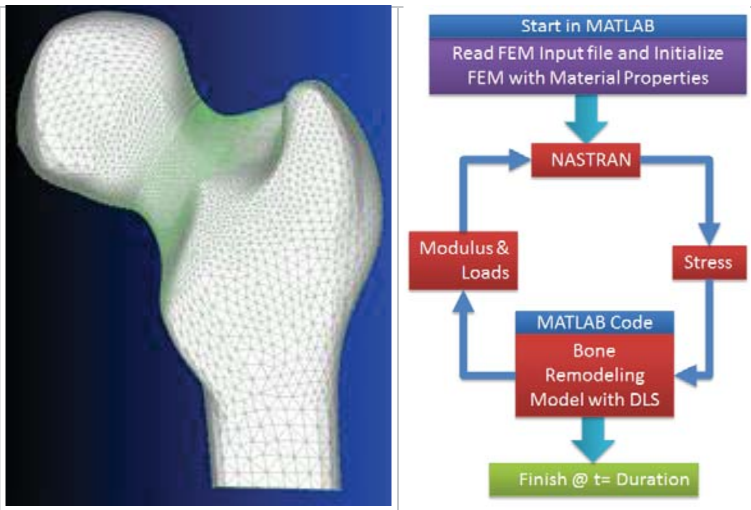

Figure 1: FEM of proximal femur (left) and block diagram of Matlab – Nastran interaction for the bone remodeling model (right)

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.

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Integration of a Finite Element Model with the DAP Bone Remodeling Model to Characterize Bone Response to Skeletal Loading

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BACKGROUND

NASA's Digital Astronaut Project Vision Statement

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

HRP Risks Knowledge Gaps Addressed by This Work

- **Osteo4**: We don't know the contribution of each risk factor on bone loss and recovery of bone strength and which factors are the best targets for countermeasure application
- **Osteo7**: We need to identify options for mitigation of early onset osteoporosis before, during, and after spaceflight.
- **Gap Fracture 3:** We need a validated method to estimate the Risk of Fracture by evaluating the ratio of applied loads to bone fracture loads for expected mechanically-loaded activities during and after a mission

OBJECTIVES

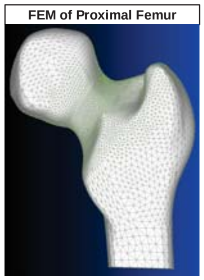
Model and Simulation Description

- 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 strains 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 included 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.

FEM of Proximal Femur



METHODS

FEM Description

- 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 stresses are used for comparison between iterations

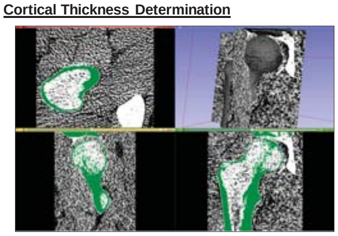
$$\|V\| = \sqrt{\left[\sum_{i=1}^{n} (\sigma_{Initial} - \sigma_{shortened})^2\right]}$$

- 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 tetrahedral elements
  - NASTRAN 101 linear static solution
  - Femap as the FEM pre and Post Processor

Initial CAD Model

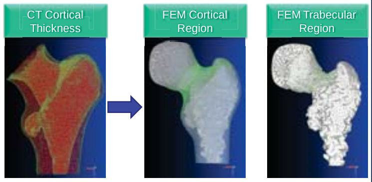
Model sliced into 1" sections

Cortical Thickness Determination



- The cortical thickness determination of the bone required publically available CT scan data and segmented using 3D slicer software (above)
- The cortical region is selected using a combination of thresholding and manual selection to segment the cortical region in the bone
- Resulting selection is exported as a raw .stl file
- The selected cortical region is then cleaned up using Meshlab software, and imported into Femap in the form of null planar elements
- Since the FEM and cortical surfaces come from two different patients, it is assumed they will not perfectly align so the cortical thickness is scaled, oriented, and aligned to the FEM
- The FEM is then manually separated using freehand selection into cortical and trabecular regions using the cortical thickness model as a guide

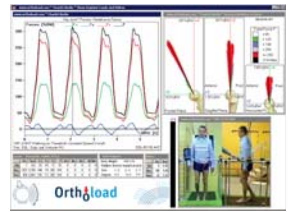
CT Cortical Thickness — FEM Cortical Region — FEM Trabecular Region

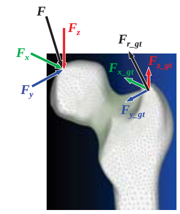


METHODS

Loads and Boundary Conditions

- The loading conditions are currently focused on mechanical stimulus due to walking and running
- Two forces are applied: joint contact force at the femoral head and muscle forces at the greater trochanter
  - Used Orthoload data for joint contact load at the femoral head [3]
  - Muscle forces were estimated based on the method of Hazelwood and Castillo [4]
- To get a better representation for the cumulative loading for a single load cycle, the mean force on the hip is used
- FEM is constrained at the base.





$$F_{x\_gt} = C_{fgt} * F_x \qquad F_{z\_gt} = C_{fgt} * F_z$$

$$F_{y\_gt} = C_{fgt} * F_y \qquad F_{r\_gt} = C_{fgt} * F$$

Where: $C_{fgt} = \left(\frac{F_{r\_gt}}{F}\right) = \left(\frac{1685}{2317}\right)$

From Hazelwood and Castillo [4]

Daily Load Stimulus (DLS)

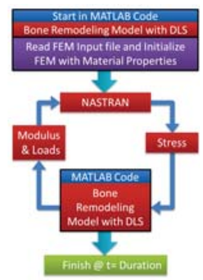
$$DLS = \sum_{j=1}^{k} S(\sigma_j, N_j, f_j, p_j, \tau_j(D_j), \omega_j)$$

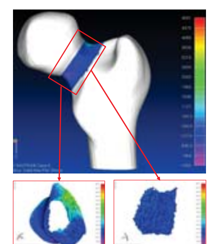
- k = The number of loading conditions/activities, or the number of exercises per day
- N_j = The number of loading cycles per loading condition or repetitions per exercise
- σ_j = Maximum principle stress per loading condition
- f_j = The load frequency of a single repetition not including pause durations between reps.
- p_j = Repetition period, including any pause periods in between repetitions
- τ_j = The ratio between the total duration of the exercise or activity (D_j), over a full day
- D_j = Total duration of the exercise or activity bout
- ω_j = Ratio of the current exercise speed over the nominal exercise speed

- The DLS is used to convert the stress, as well as other parameters, to a singular useful value for the bone remodeling model
- To develop this new formula, we conducted an extensive study to evaluate existing DLS formulas [5]

Bone Remodeling Integration

- The FEM is integrated by:
  - Receiving the modulus and load values from the remodeling algorithm
  - Determining the resultant stresses / strains
  - Passing them back to the remodeling simulation to calculate mechanical stimulus
- Nastran can be run multiple times throughout the simulation to update the load path due to changes in cortical and trabecular stiffness





Cortical bone — Trabecular bone

MODEL VERIFICATION AND VALIDATION

Verification

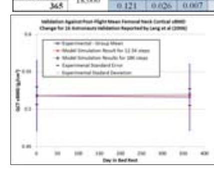
- Analysis on change in bone density due to normal daily walking for different body masses and steps per day
- Results show no change in density with small decreases for minimal steps per day cases

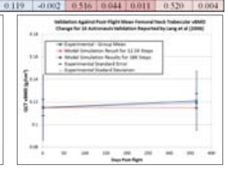
Weight (N)	Steps	Duration (days)	Trabecular vBMD (g/cm³) Initial	Final	Change	% Change	Cortical vBMD (g/cm³) Initial	Final	Change	% Change	DXA aBMD (g/cm²) Initial	Final	Change	% Change
791	5000	365	0.131	0.130	-0.001	-0.76%	0.532	0.531	-0.001	-0.19%	0.891	0.891	0.000	0.00%
	7500			0.131	0.000	0.00%		0.532	0.000	0.00%		0.891	0.000	0.00%
	10000			0.131	0.000	0.00%		0.532	0.000	0.00%		0.891	0.000	0.00%
565	5000			0.129	-0.002	-1.53%		0.528	-0.004	-0.75%		0.889	-0.002	-0.22%
	7500			0.131	0.000	0.00%		0.531	-0.001	-0.19%		0.891	0.000	0.00%
	10000			0.131	0.000	0.00%		0.532	0.000	0.00%		0.891	0.000	0.00%

Validation

- Assumed that astronauts are likely to engage in higher daily activity that would be the equivalent to 12,500 to 18,000 steps
- Mean body weight of 725 N and walking speed of 5km/h was assumed
- The simulation results match the data reported by Lang et al [6] 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 [6]

Duration (days)	Number of steps	Trabecular Experimental [7] Mean	SD	SE	Model Output	Error	Cortical Experimental [7] Mean	SD	SE	Model Output	Error
Post-flight	12,500	0.115	0.029	0.007	0.115	-	0.518	0.047	0.012	0.518	-
365		0.121	0.026	0.007	0.115	-0.006	0.516	0.044	0.011	0.518	0.002
Post-flight	18,000	0.115	0.029	0.007	0.115	-	0.518	0.047	0.012	0.518	-
365		0.121	0.026	0.007	0.119	-0.002	0.516	0.044	0.011	0.520	0.004





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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