BONE MINERAL DENSITY MAINTENANCE DURING LONG-DURATION SPACEFLIGHT

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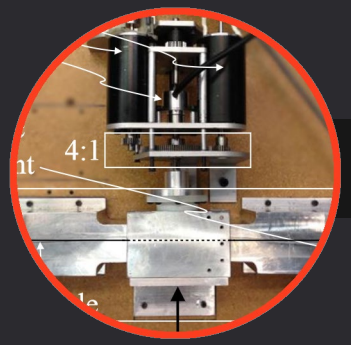
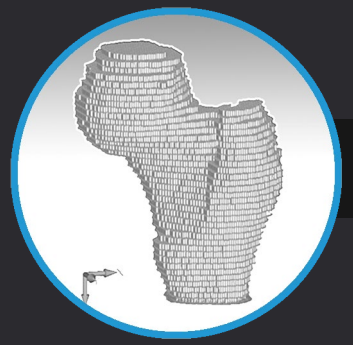
ABOUT ME

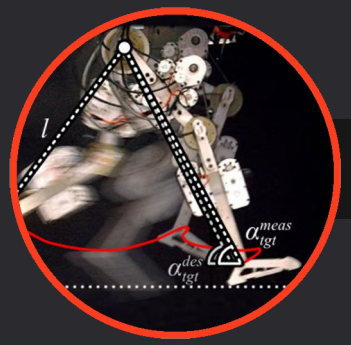
2009: CWRU Cutter



2014: Compact Nonlinear Springs



2017: Computational Modeling



2010: Robotic Neuromuscular Leg

2016: Modular Series Elastic Actuators

WHAT IS NASA CCMP?

- The Cross-Cutting Computational Modeling Project (CCMP) is located within NASA's Human Research Program (HRP).
- We seek to fuse traditional research with computational modeling to better characterize risks and improve decision making for human spaceflight.

NASA's Cross-Cutting Computational Modeling Project logo.

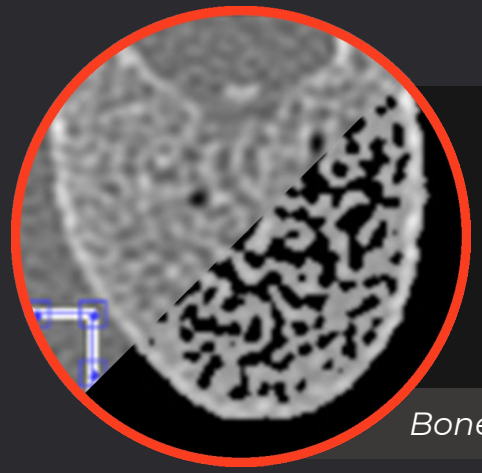
- Machine learning is currently used to support HRP efforts in areas related to in-flight, in-mission, and long-term medical risk assessment.
- Machine learning has further application to unique health and performance concerns and specific human physiology changes during spaceflight.

NASA's Human Research Program Logo

RESISTIVE EXERCISE PREVENTS BONE LOSS DURING SPACEFLIGHT

- Astronauts experience 0.4-2.7% monthly volumetric bone mineral density (vBMD) loss during long-duration missions.
- Resistive exercise counters the effects of microgravity, but the required exercise frequency and duration for individuals is unclear.

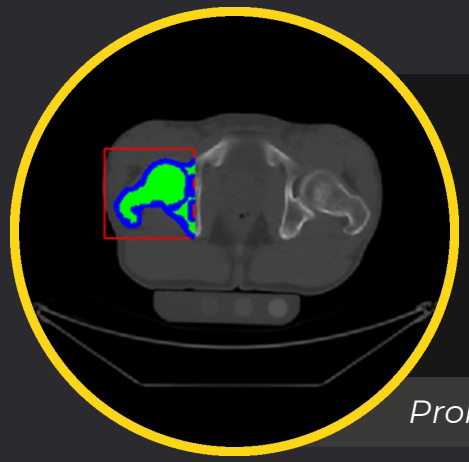
The Hybrid Ultimate Lifting Kit (HULK) exercise device during parabolic flight.



- Personalized computational models may provide insight into the required amount of exercise for vBMD maintenance.
- Subject-specific bone finite element (FE) models are required for these models, but generating them can be slow and laborious.

Bone CT cross section. L: Raw, R: Pixel-based thresholding segmentation.

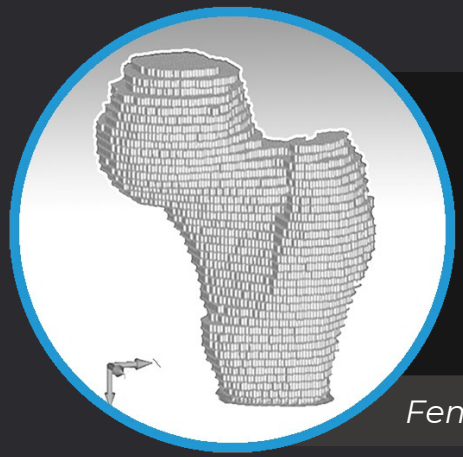
BAYESIAN CLASSIFIERS CAN AUTOMATE FE MODEL GENERATION



Given: $X^{new} =< X_1, ..., X_n >$

Classify: $\hat{y} = \underset{j \in \{1,...,J\}}{\operatorname{argmax}} \propto P(Y = y_j) \prod_{i=1}^{n} P(X_i^{new} | Y = y_j)$

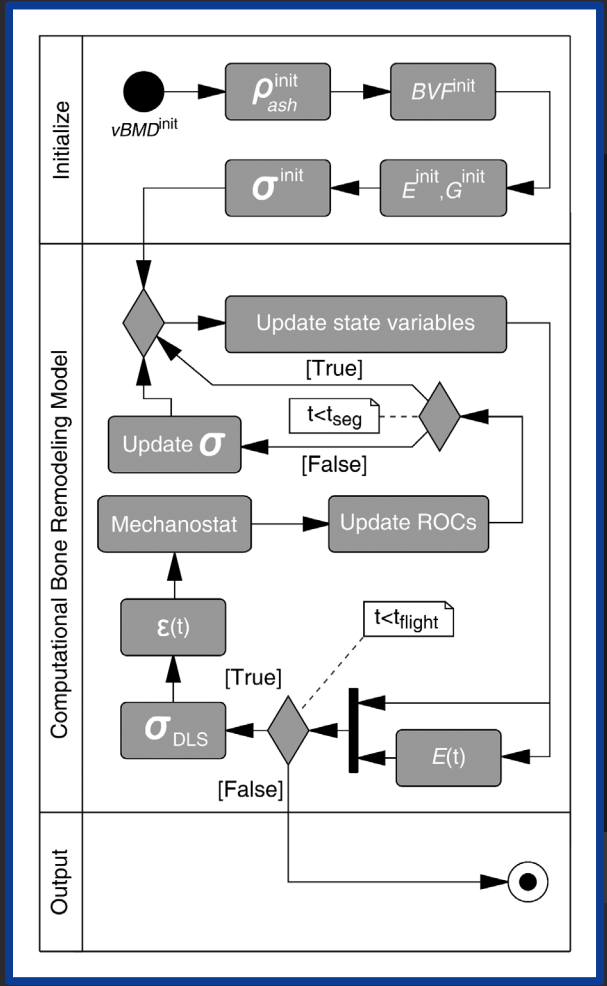
Probabilistic segmentation result of a DICOM CT image slice.



- The probabilistic classification scheme successfully segments bone containing images into 3 material types, requiring minimal post-processing.
- The Bayesian classification scheme decreases the required time to build a subject-specific FE model from 8 hours to 10 minutes.

Femur FE model generated from segmented CT image slices.

NASA'S BONE MODEL RELATES vBMD TO LOAD INDUCED STRESSES



- NASA has developed a bone remodeling dynamics model to estimate changes in vBMD in response to skeletal unloading and exercise.
- The model is initialized from CT image data and estimates mean cortical and trabecular bone mineral density as a function of time.
- Chemical remodeling rates are related to the aggregate daily bone strain resulting from exercise via Frost's mechanostat theory [1].
- Bone strain can be calculated for specific resistive exercises via the *daily load stimulus*, a relationship that relates induced single-cycle cortical and trabecular stresses to the frequency and number of exercise repetitions [2].

Overview of the computational bone remodeling model.

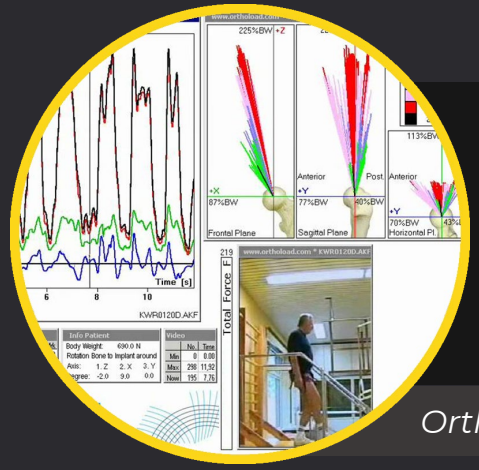
[1] Frost, H. M. (2003). Bone's mechanostat: A 2003 update. *Anatomical Record Part A: Discoveries in Molecular, Cellular, and Evolutionary Biology.*
[2] Turner, C. H. and Robling, A. G. (2003). Designing exercise regiments to increase bone strength. *Exercise and Sport Sciences Reviews.*

ANALOG BEDREST STUDY DATA IS USED TO VALIDATE THE MODEL

- The computational bone model is evaluated using data from subjects participating in a spaceflight analog 70-day bed rest study.
- A subset of participants performed exercises consistent with NASA's integrated resistance and aerobatic training regimen (iRAT) study [3].

Vertical treadmill in the NASA Flight Analog Research Unit.

[3] Ploutz-Snyder, L. L. *et al.* (2014). Integrated resistance and aerobic exercise protects fitness during bed rest. *Medicine and Science in Sports and Exercise.*

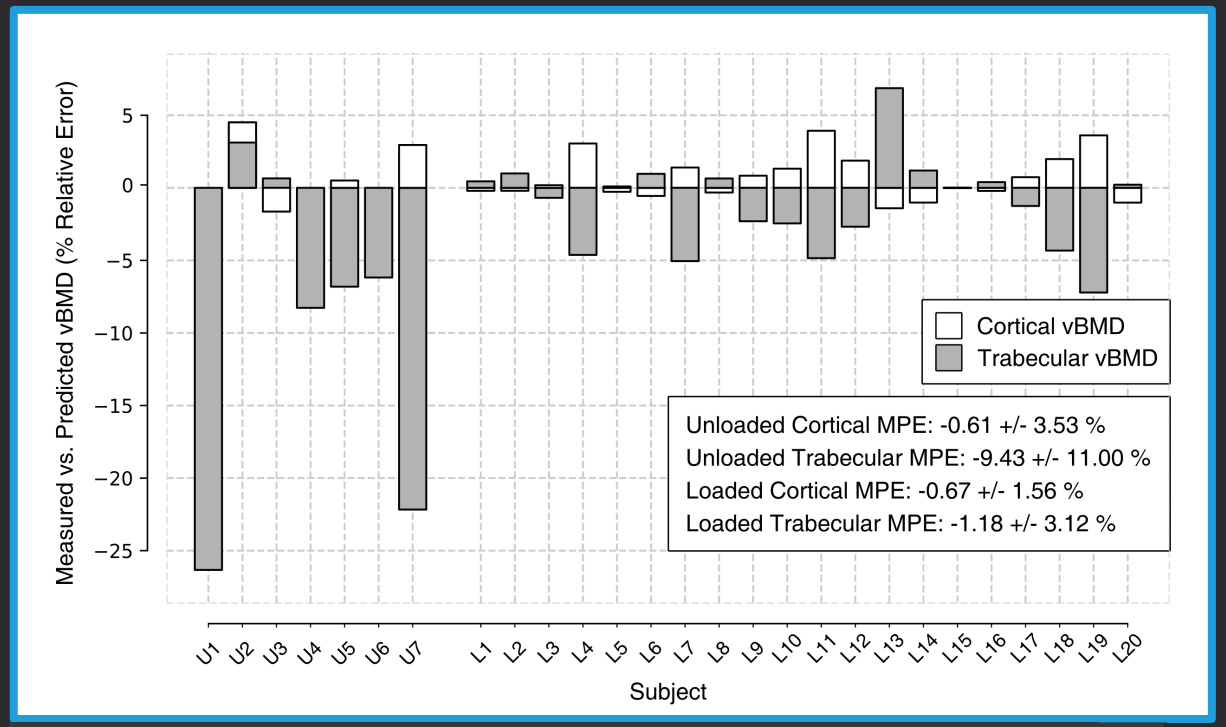


- The required vBMD maintenance force is assumed to be equivalent to femoral head contact forces resulting from walking 5,000 steps per day [4].
- Stochastic optimization of femoral head contact forces is used to simultaneously test model convergence and evaluate model behavior.

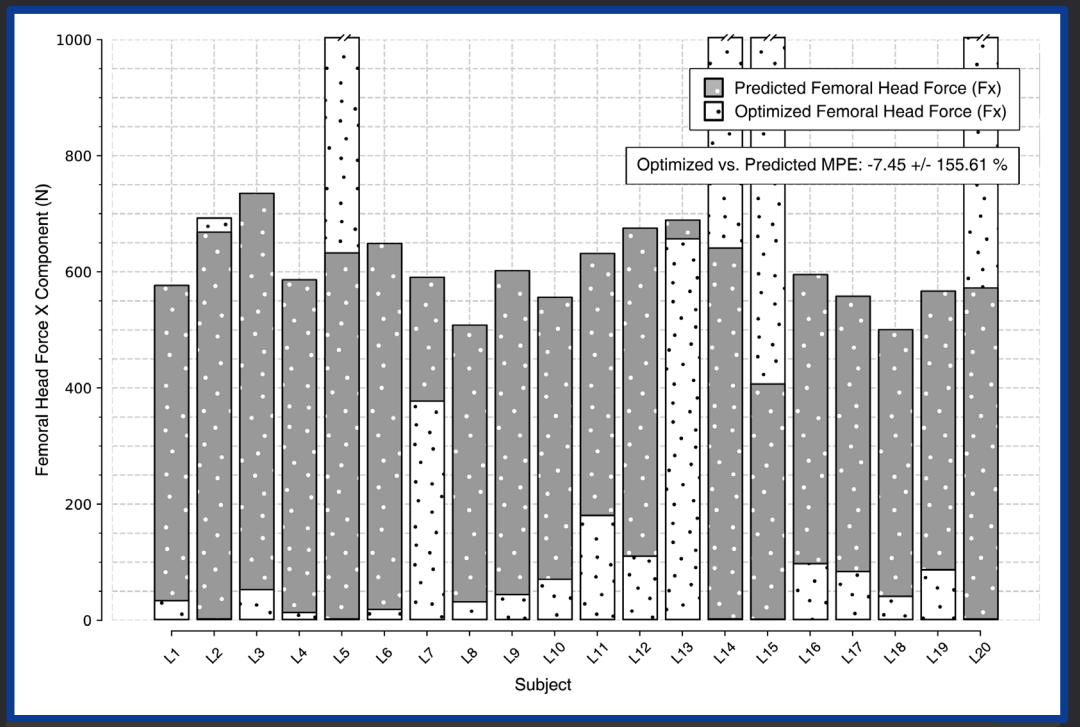
Orthoload public database.

[4] Bergman, G. (2008). Orthoload. Charité Universitätsmedizin Berlin. http://www.OrthoLoad.com.

MODEL PREDICTS POST-STUDY VBMD, BUT FORCES ARE LOW

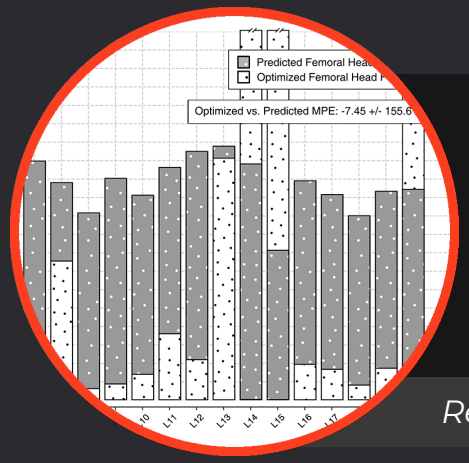


Measured vs. predicted post-study vBMD. U: Unloaded. L: Loaded



Regression vs. model predicted vBMD maintenance forces.

FUTURE WORK FOCUSES ON QUANTITATIVE FORCE PREDICTION



Regression vs. model predicted vBMD maintenance forces.

- The model predicts post-study vBMD of subject with a low mean relative error, but predicted forces only qualitatively show the benefits of exercise.
- This behavior likely results from the use of a single remodeling model parameter set and the same FE bone model for all subjects.

The Advanced Twin Lifting and Aerobic System (ATLAS).

- Ongoing research is investigating further personalization, including subject-specific parameters and bone geometry changes during flight.
- This research is being used to inform the design of ATLAS, a general-purpose robotic exercise device for use in microgravity environments.