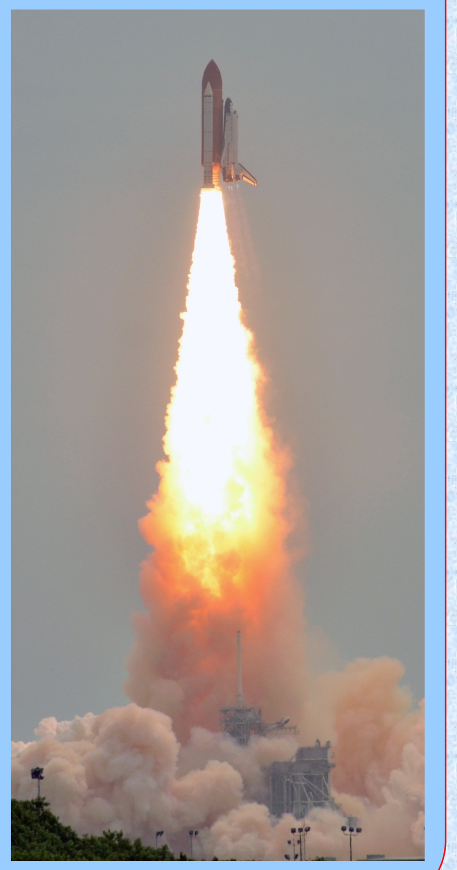
Effects of Microgravity on Effective Stiffness of Bone

Colin T. Smith[1], Anthony G. Lau[2], Eric W. Livingston[2], Laura C. Bowman[2], Ted A. Bateman[2]
[1]North Carolina State University Department of Mechanical and Aerospace Engineering
[2]University of North Carolina at Chapel Hill Department of Biomedical Engineering

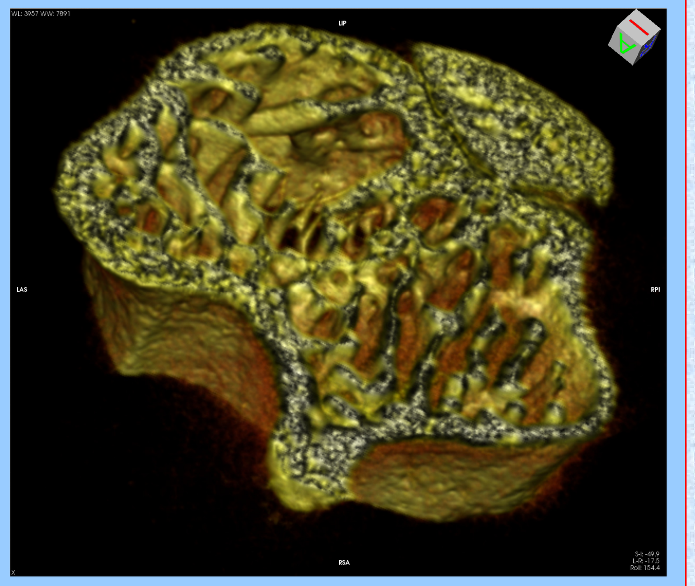
Introduction

Studies and experience in spaceflight has shown that the absence of gravity in the skeleton will cause severe and rapid declines in total bone mass. As a result, the effective stiffness of the bone is greatly compromised. This study examines this effect on the tibiae of mice flown on the STS-135 mission using microCT images imported into Abaqus/CAE to evaluate changes in strength due to microstructure. Effective bone stiffness in a compression test is a good clinical measurement of bone performance in a patient. Optimizing the compressive stiffness of a bone would help astronauts avoid injury during missions to Mars and patients suffering from degenerative bone disease on earth.



Methods

Imaging and Voxel Conversion



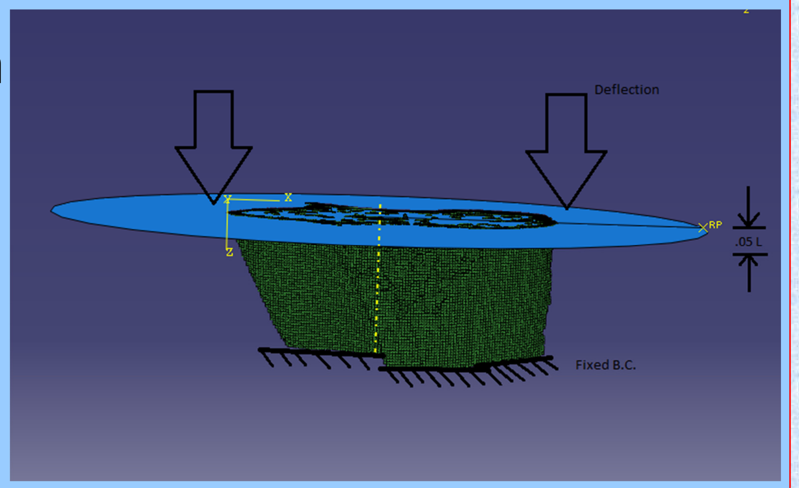
1. A 1.0 mm thick section of proximal tibia just inferior to the growth plate was scanned at 10 micron resolution using a Scanco µct80.
2. Bone elements were thresholded and assigned linear elastic material properties (E= 10 GPa, v = 0.35).

Model Pre-Processing

3. A mesh was directly exported from microCT data down sampled to 20µm element size and imported to ABAQUS CAE.
4. An analytical rigid loading plate was created.
5. The analytical rigid plate surface and superior nodes of the bone were paired for contact interaction definition.
6. Boundary conditions were prescribed by fixing inferior nodes and displacing the analytical rigid plate by 5% of the total thickness of the bone (50µm).
7. The model was run using ABAQUS Standard (implicit solver).

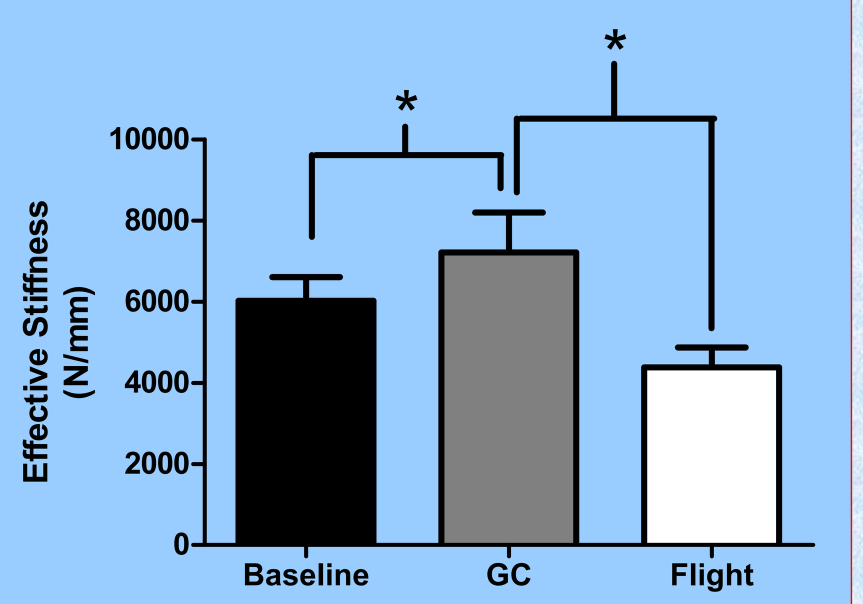
Mesh Quality Analysis

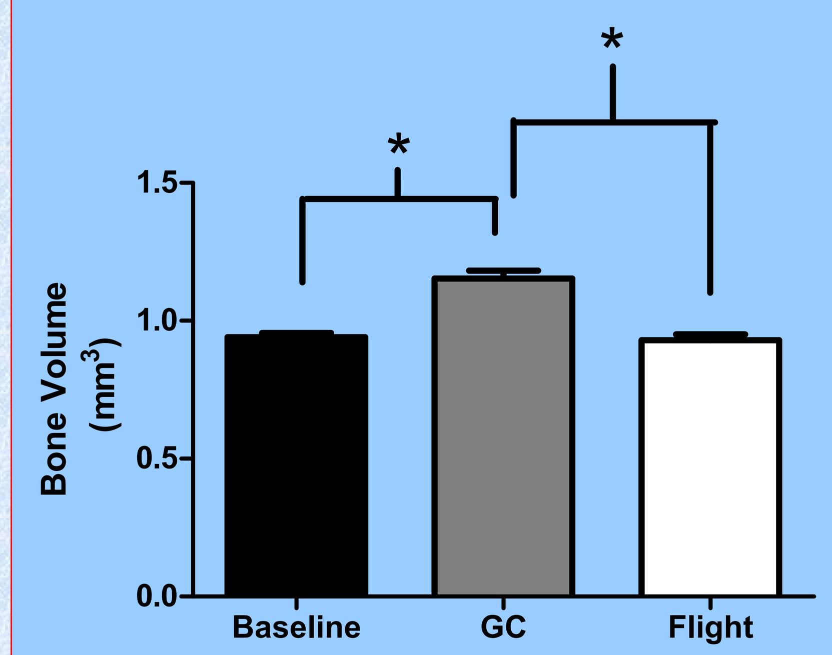
Analysis was run on models at 20 µm since it was determined that the resultant forces were within 2% error for each model compared to 10 µm elements. This was done to conserve computational power and time.



Results

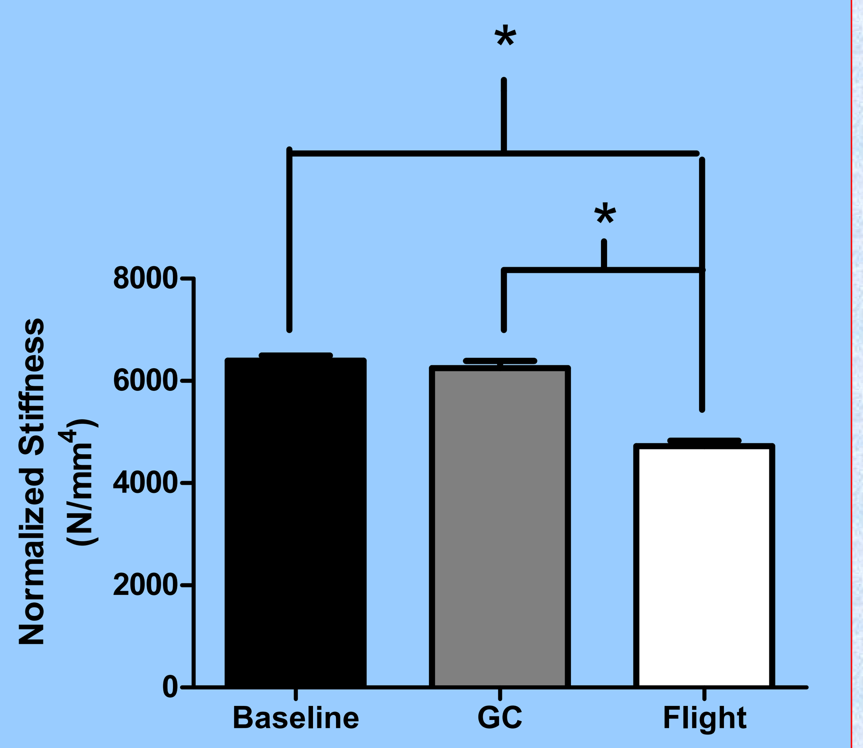
The ground control (GC) group had 20% stiffer bone than the baseline. The flight group had a 39% decline in bone stiffness compared to the ground control. Both of these sets of data are statistically significant.



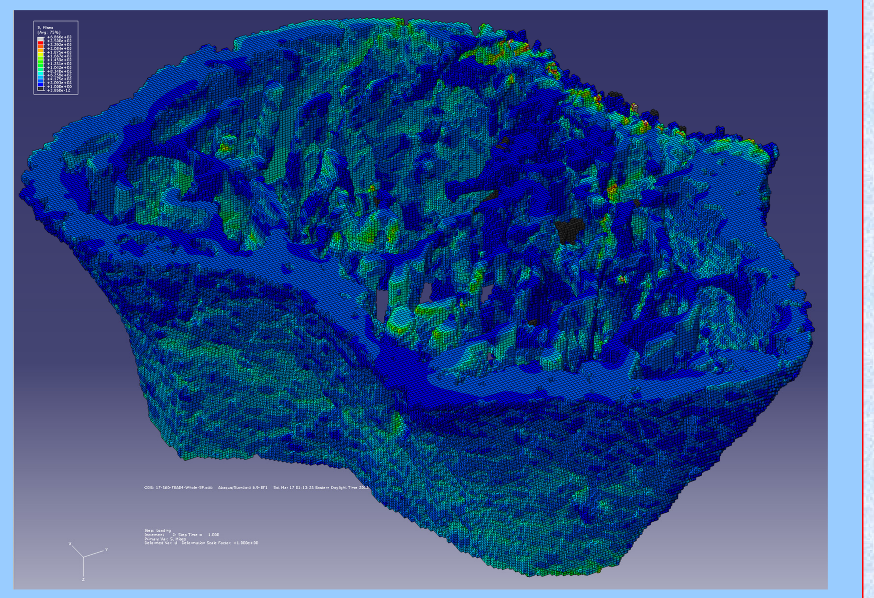


The means values for the total bone volume of each sample was calculated. The ground controls were 14% higher than baseline, while flight decreased by 4% compared to baseline.

Normalized stiffness was determined by dividing the effective compressive stiffness by the bone volume. This describes how efficiently the bone structure bears load. There was no significant change between the ground control and baseline groups.



The load distribution on the trabeculae can be observed. Ground control bones had thicker and more numerous trabeculae, and therefore less areas of high stress in individual trabeculae compared to those of the flight group.



An elastic model falsely indicates high stress in some regions of the trabecular structure that would be otherwise subject to buckling and fracture, which could lead to a further decrease in effective stiffness.

Discussion

Interpreting the Results of this Study

These results show flight severely compromised the stiffness of bone as well as contributed to loss of total bone mass. Using FEA we were able to investigate how these two parameters are related.

The data illustrates that as young mice age under normal conditions, the strength and mass of their bones increase. Spaceflight causes a 39% reduction in stiffness with only an 18% reduction in volume. Stiffness is reduced much more dramatically because much of the contribution of overall stiffness comes from trabecular bone structure which comprises much less of the total bone than the cortical shell. During spaceflight, bone resorption is increased, so trabecular structure is lost, thus compromising the effective stiffness in a compounding manner. Normalizing stiffness to bone volume helps illustrate this trend. Normalized stiffness should not change over the normal life of one mouse. However, according to this study there was a decline in this value.

Addressing the Problem

This problem inhibits development of human space travel in that the average traveler would not be able to easily cope with the issue. Astronauts aboard the ISS engage in intense workouts but succumb to the effects upon landing. Anti-resorptive drugs could demonstrate an ability to promote normal bone turnover even in a weightless environment. Perhaps nanotechnology could provide structural material for this application.

Future Research

In addition to the tibiae of the mice in this study, the femora were imaged as well. If a model capable of accounting for the more complex geometry of the femoral neck could be developed, then the data could be compared to the tibiae for more insight on the effects of spaceflight on the skeletal system. A plastic model could be imaged and analyzed to more accurately simulate the role of trabecular structure.

Acknowledgments

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