Computational Modeling of Adaptive Bone Healing During Physical Rehabilitation

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INTRODUCTION

- 10-12% of skeletal injuries do not heal by themselves within nine months of fracture due to wound size[1].
- Physical rehabilitation can introduce mechanical stimuli that promote bone healing if it is not too aggressive[2].
- It is difficult to experimentally measure whether a physical rehabilitation program introduces the right amount of compression during physical rehabilitation.

This study aimed to measure compressive strain throughout bone fractures during exercise associated with different physical rehabilitation programs.

HYPOTHESIS

We hypothesized that we could accurately measure compressive strain across healing femurs by using subject-specific micro-CT images.

METHODS

Experimental Study

- Surgical cuts (2 or 3 mm) were made in rat femurs leaving behind defects with only soft tissue remaining (Fig. 1A).
- Femurs were stabilized with fixator plates embedded with wireless strain sensors (Fig. 1B).
- Rats were given 1 of 3 rehabilitation programs (Fig. 1C).
  - In-cage: Kept in wheeled cage with limited wheel access.
  - Out-of-cage: 2 hrs. of wheel access per day.
  - Unrestricted wheel access.
- Femurs were imaged via micro-CT at 2 weeks after surgery.

Computer Modeling

- Geometry: Subject-specific defect geometries were generated from micro-CT images and imposed on a generalized model of a rat femur (Fig 2A).
- Stiffness assignment: The stiffness of the bone varied spatially based on the intensity of the micro-CT image.
- Boundary Conditions:
  - The bottom of the femur was fixed in place (Fig 2B).
  - A force was applied to the top of the femur until the strain in the sensor matched experimental measures. (Fig. 2C, 2D).

RESULTS

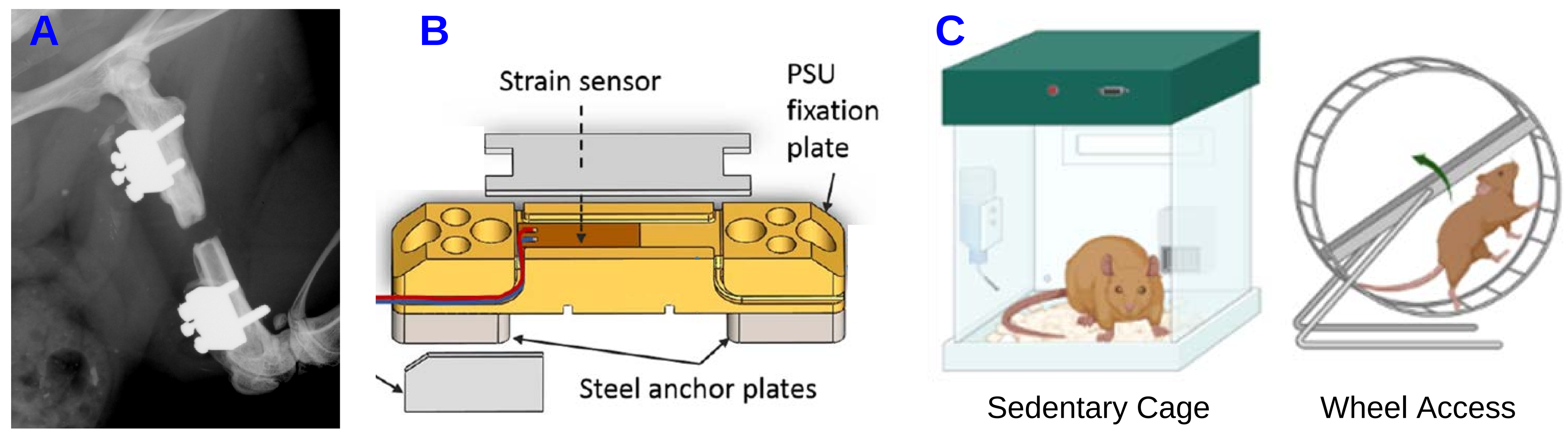

Figure 1. (A) X-ray image of a surgically induced fracture femur of a rat. (B) Custom-made compliant fixator to stabilize fractured femur and measure resulting strain during activity. (C) A cage is used to keep rats sedentary, and wheels are provided to allow voluntary rehabilitative exercise.

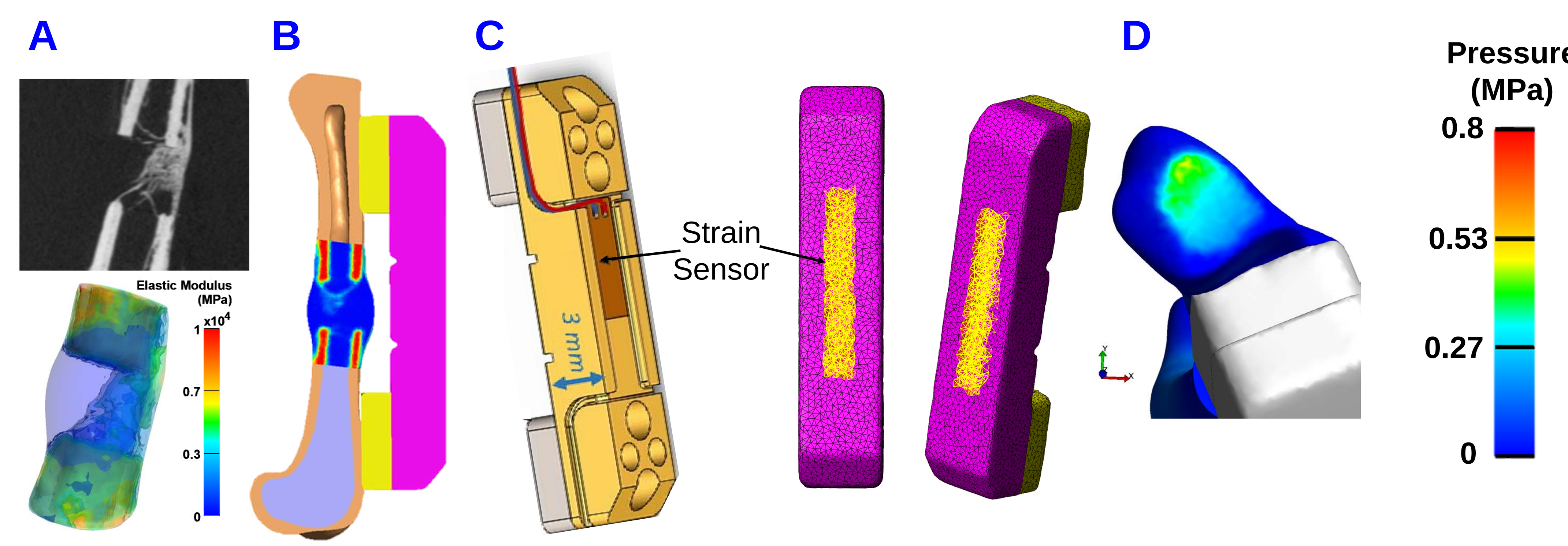

Figure 2. (A) Segmentation and material assignment of the defect from micro-CT scan images (B) Side view of femur-sensor plate assembly. (C) Experimental strain at the back of the fixator plate is compared with simulation outcome to determine applied load. (D) Spatially varying load applied at the proximal end of the femur.

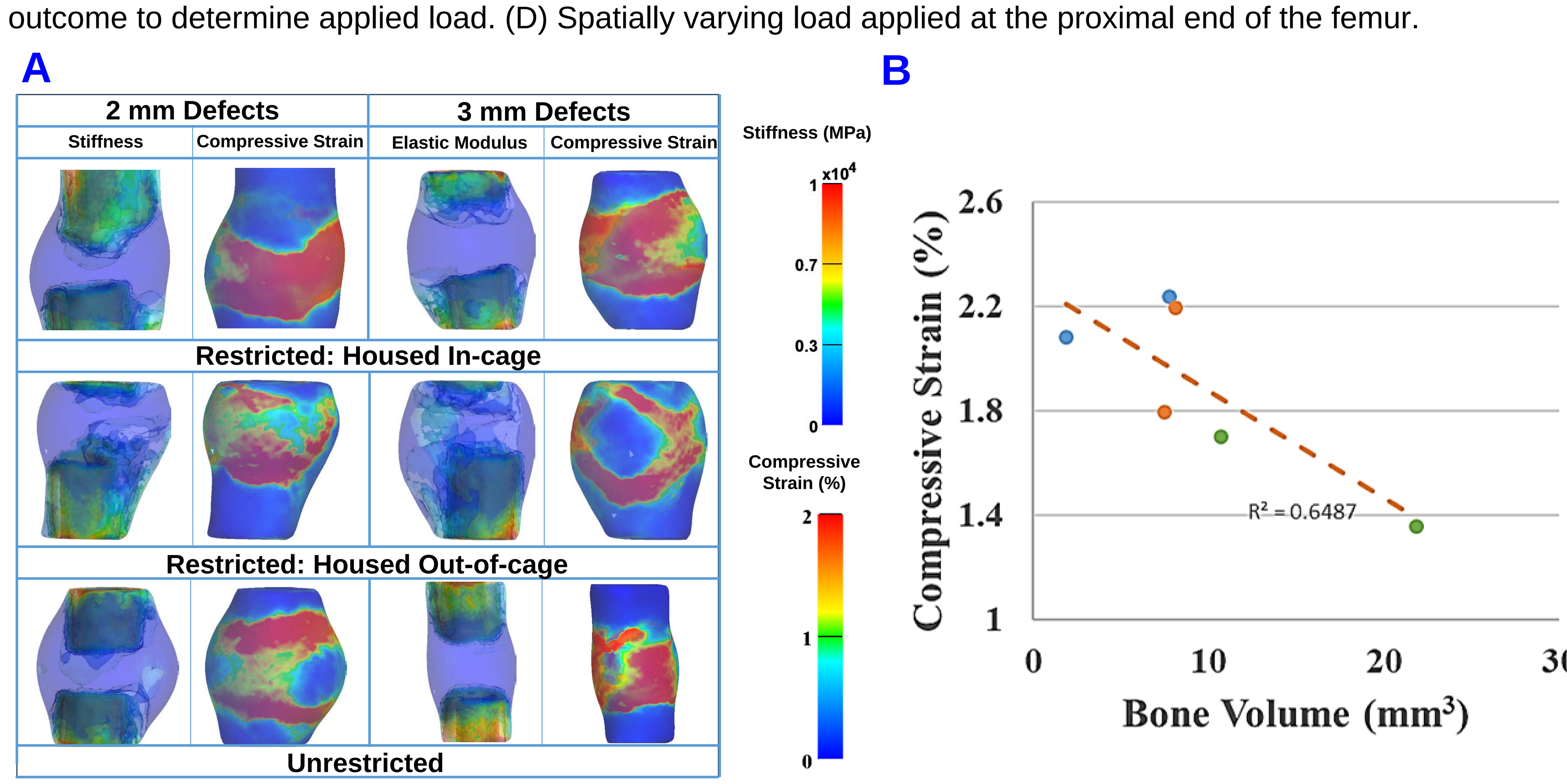

Figure 3. (A) Plots of the distribution of the soft tissue stiffness and compressive strain across the defect at four weeks post-surgery. (B) Larger bone volume at the defect region caused lower compressive strain as the amount of soft tissue is lower.

DISCUSSION

- The activity parameter of the rats depends on the defect size and the rehabilitation processes they go through. This significantly affects the end-point bone volume.
- Image mapping can capture the elastic modulus of the defect based on the intensity of micro-CT scan images. As the intensity represents the mineralization at the defect, we could recreate the local environment in our simulation (Fig. 2A).
- The femur's elastic modulus significantly affects the defect strain. It was validated using reaction forces that matched experimental values.
- The compressive strain distribution heavily depends on the mineralization at the defect. At the 4-week time point, higher mineralization resulted in lower compressive strain and vice versa (Fig. 3B).

CONCLUSION

- The rehabilitation process has a crucial role in determining the outcome of the bone healing process.
- We developed a workflow that measures subject-specific compressive strain throughout fractured bone regions.
- This workflow can be used to understand how different physical rehabilitation programs affect endpoint bone volume.
- This will enable rehabilitation processes tailored to each patient to ensure optimal bone healing outcomes.

ACKNOWLEDGEMENTS

We acknowledge financial support from NIH R01AR069297.

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