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Classical Beam Theory Provides Reasonable Estimates of Interfragmentary Motion in Dynamic Simulations of Distal Femur Fracture Reconstructions

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Introduction

Distal femoral fractures are debilitating injuries that typically require surgical intervention to repair. Proper healing requires secondary callus formation, which is promoted by axial interfragmentatry motions but inhibited by shear displacements.[1] Locking plates are often used to address these injuries, and surgeons can attempt to tune the stiffness of the reconstruction with bridge-plate fixation techniques. It is known that increasing the distance between the two closest screws on a plate, "bridge span" (Figure 1) will decrease the stiffness of the repair. Bridge plating in distal femoral fracture reconstruction is an inexact science, which is evidenced by a recent clinical study that had a 19% re-operation rate.[2] Benchtop experiments and finite element models have been developed to characterize the interfragmentary motions associated with bridge-plate reconstructions of the distal femur, but these experiments are costly, time consuming, and often only quantify the mechanics of the repair during a single pose under static or quasi-static load. To date, it is thought that patient-specific preoperative assessment of the mechanical environment for callus formation remains impractical.

The purpose of this study was to develop a computational musculoskeletal model that could provide estimations of the forces and moments that are experienced at the fracture site during a dynamic task. With this information in hand, we utilized simplified representations of locking plates (using uniform beam theory) to make estimations of the interfragmentary displacements associated with a specific subject and activity. We hypothesized that this rudimentary model may provide reasonable approximations of implant deflections and relative displacements between bones.

Methods

Loading biomechanics at the fracture site were simulated using a musculoskeletal model of a 50th percentile male during the stance phase of walking.[3] A transverse fracture of the distal femur was virtually created by adding additional coordinate systems to the right femur of the model. This fracture was iteratively created between 50-90% (1% increments) the distance from the proximal to distal length of the femur (Figure 1). To account for the lateral placement of surgical plates, the 'fracture' coordinate system was placed on the lateral cortex of the femur. Muscle forces were estimated using a static optimization algorithm to generate the joint loads necessary to produce the motion of walking. These muscle forces were then combined with ground reaction forces to estimate the loading biomechanics at the lateral surface of the fracture site, a surrogate measure of the loads that would be experienced at the mid-point of the locking plate implant.

Estimations of plate bending were performed using Euler–Bernoulli beam theory.[4] Implants were represented as rectangular bars with a cross section of 18mm × 4mm. Material properties were assigned as either stainless steel (316L; E = 193GPa) or medical grade titanium (Ti6Al4V; E = 113.8GPa). Bridge spans, or working lengths of the beams, were varied between 20-180mm in 10mm increments. The fixation on both ends of the beam were assumed to be simply supported. Axial loads, shear loads, and in-plane moments (determined from the dynamic simulations) were applied to the beam at the midpoint. Maximum displacements were calculated for every trial and results were summarized.

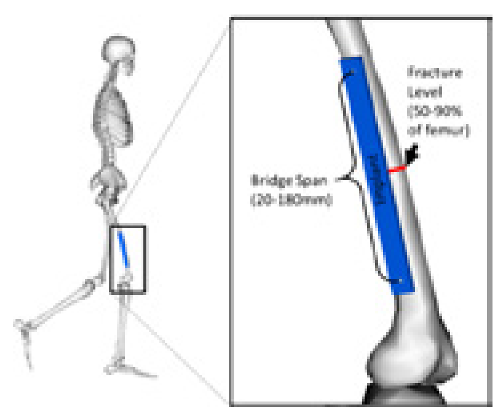

Figure 1. Representative images from the musculoskeletal model showing a subject during stance. Changes to the level of the femoral fracture, implant material, and bridge span led to differences in implant deflection.

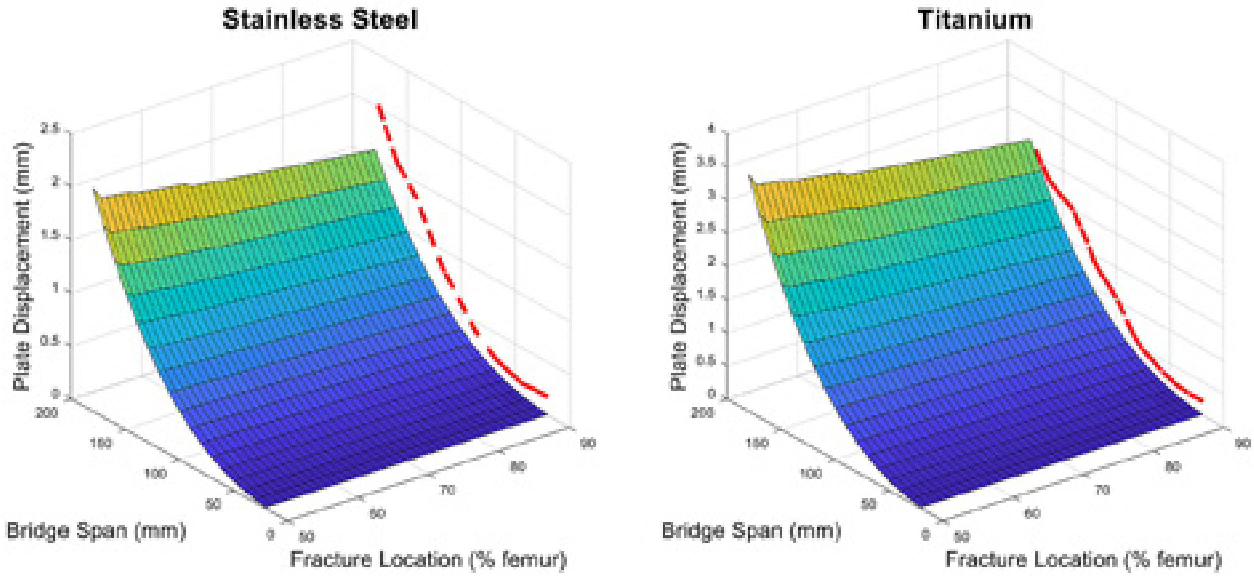

Figure 2. Outputs of the simulations for stainless steel (left) and titanium (right) beams. The red dashed lines represent outputs from a previous finite element study [CIT]. Root mean squared errors between simulations and the previous study are shown above.

Results

The estimated plate displacements increased in a non-linear fashion as a function of bridge span (Figure 2). The magnitudes of displacements were distinctly different for the stainless steel and titanium plates. Specifically, the stainless steel plates had a maximum deflection of 2.10 mm in the simulation that utilized a 50% fracture location and a bridge span of 180mm (Figure 2A). The titanium plate simulations had a maximum deflection of 3.57mm in the same scenario. When simulations outputs were compared to an existing finite element model[5] that related transverse deflection of distal femoral locking plates (~90% fracture location) to bridge span during standing, the stainless steel simulations had an RMSE of 0.32mm, while the titanium simulations had an RMSE of 0.33mm. Assessment of all 1394 individual simulations of gait took less than one minute of computational time on a PC with an i7 3.6GHz processor and 16 GB of RAM.

Discussion

This patient-specific dynamic model provides a fast but coarse estimation of implant deflections. Given the number of assumptions that were made, the outputs provide fairly reasonable approximations of implant deflections and provide insight into interfragmentary motions. The current model only represents a walking motion of a 50th percentile male, but results would change with alterations to body mass, activity, and implant material, and implant cross-sectional geometry. Because preoperative gait assessment after a distal femoral fracture is not possible, a library of simulation results could provide surgeons with a lookup table (based on body mass, activity level, implant geometry, and fracture location) to determine an appropriate bridge span. This framework could be readily adapted to assess locking plate behavior on other bones of the body.

Clinical Relevance

Preoperative utilization of this modeling paradigm could potentially improve a surgeon's "best guess" to optimize the mechanical environment for callus formation to occur.

References

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