FINITE ELEMENT MODEL EVALUATION OF A PERCUTANEOUS TECHNIQUE FOR REPAIRING PROXIMAL FEMORA WITH METASTATIC LESIONS

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INTRODUCTION: Metastatic lesions in the proximal femur are a common and often painful manifestation of breast cancer that can lead to pathologic fracture. A proposed minimally invasive procedure for preventing fracture involves removing the lesions and injecting bone cement (polymethylmethacrylate) into the remaining defects via a drill hole through the lateral aspect of the greater trochanter (Fig. 1a). The structural feasibility of this procedure was demonstrated in a study on cadaveric femora with burred defects representing metastatic lesions. However, mechanical testing using matched pairs of femora only allowed for comparison of hip strength after repair (S\text{repair}) with hip strength of the contralateral intact femur, which was used as an estimate of the strength of the ipsilateral intact femur (S\text{intact}). Comparison of these measures with hip strength of the femur with the unrepaired defect (S\text{unrepaired}) was not possible. In contrast, use of finite element (FE) modeling would enable a well-controlled study in which all three strength values could be compared for each femur. CT scan-based FE models can predict the strength of proximal femora both with and without metastatic lesions, although the validity of these models for predicting the strength of femora injected with bone cement is unknown. Therefore, the goals of this study were (a) to validate FE-model predictions of hip strength for femora containing bone cement; (b) to use the validated FE models to evaluate the structural deficit caused by defects at several locations within the femoral neck; and (c) to evaluate the effectiveness of the proposed surgical technique for repairing those defects.

METHODS: Twelve matched pairs of cadaveric proximal femora were obtained from female donors. For FE validation, a roughly spherical defect, measuring approximately 75% of the neck diameter, was burred into the neck of one randomly selected proximal femur from each pair. The defects were randomly placed in the superolateral (SL), inferomedial (IM), anterior (A), or posterior (P) aspect of the neck (three femora with each defect site) (Fig. 1a), and were approximately tangent to the periosteal surface, ensuring that the cortex was substantially eroded. The burred defects were then repaired using the percutaneous procedure described previously.

Each repaired and contralateral intact femur was CT scanned. A three-dimensional FE model of each femur was generated from the CT scan data using nonlinear mechanical properties. Cement was assigned mechanical properties for Simplex P bone cement (E=2720 MPa, S=98 MPa). The modeled boundary conditions represented single-limb stance-type loading, with displacement applied to the femoral head at 20° to the shaft within the coronal plane. The FE-predicted fracture load, F\text{FE}, was defined as the maximum total reaction force at the femoral head. The femora were mechanically tested to failure under the modeled loading conditions and the measured fracture load for each specimen, F\text{meas}, was the maximum load achieved. Validity of the FE models of the repaired femora was assessed by using ANCOVA to compare simple linear regression equations between F\text{meas} and F\text{FE} for the intact and repaired femora.

After FE model validation, 6 FE models were created from the CT scan data of each of the 12 intact femora. In-house software was developed to simulate 20-mm-diameter spherical defects at each of six cortical locations: SL, IM, A, and P (the burred defect sites used previously); one centered within the neck (Center), and one in the dense trabecular bone near the base of the femoral head (Head) (Fig. 1b). F\text{FE} for each model with a simulated defect was divided by F\text{FE} of its respective intact FE model to obtain a measure of the strength remaining after introduction of the defect, S\text{intact}/S\text{unrepaired}.

The software was also used to simulate the repair procedure by modeling the cement-filled defect and drill hole. For each of the defect locations, the six femora with the lowest S\text{intact}/S\text{unrepaired} were identified, and the repair procedure was simulated. F\text{FE} for each repaired FE model was divided by F\text{FE} of its respective intact FE model to obtain a measure of the structural viability of the repair technique, S\text{repair}/S\text{intact}. The mean and standard deviation of S\text{intact}/S\text{unrepaired} and S\text{repair}/S\text{intact} were calculated.

RESULTS: One repaired femur was removed from the data analysis after it was discovered to have a fracture prior to mechanical testing.

DISCUSSION: The significance of the regression equations for the intact and repaired femora indicates that the presence of bone cement in the repaired femora does not affect the validity of the FE models, and the similarity between the equations allows the strength predictions for the intact and repaired femora to be compared.

This study has shown that the proposed percutaneous repair technique can completely restore the strength of proximal femora with 20-mm-diameter simulated metastatic lesions in the femoral neck. Defects in the IM aspect of the neck caused the greatest decrease in bone strength, an effect probably due to direct load transmission through this region. However, the repair technique successfully restored strength even in cases with such severe structural deficits. These results are consistent with the mechanical testing results of repaired femora after consideration of slight differences in defect sizes and locations.

This study examined the effects of 20-mm-diameter defects in the femoral neck. However, the effects of defects and the efficacy of the repair technique at other locations, such as the subtrochanteric region, should be evaluated. Failure from fatigue (repetitive loading) was not examined, so our results apply only to static (single load to failure) loading conditions. The idealized shape of the defects did not reflect the irregular borders of metastases and did not represent interdigitation of cement and bone, which occurs during pressurization, so our results must be considered approximate. The bone-cement interface presents a complex mechanical and biological environment that may be a potential source of failure, so this region will need to be investigated. Finally, since the effect of defects on bone strength varied with position in the femoral neck, a better understanding of how defects placed around this region affect bone strength may lead to improved clinical guidelines for predicting fracture risk.


ACKNOWLEDGEMENTS: This study was funded by DOD BCRP DAMD 17-02-1-0325. Bone cement and associated instruments for preparation and delivery were generously provided by Stryker Corp.