Influence of Osteolytic Lesions on the Fracture Process of the Proximal Femora

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Osteolytic lesions form when metastatic cancer spreads to bone and causes tissue to decay, increasing the risk of pathological fractures. This study aims to provide medical professionals with a guide for determining whether to operate on a femur with detected lesions. 3D-generated Finite Element Analyses were performed on femur models in Abaqus to mimic a stance position. The force required for fracture and stiffness of the bone were extracted from each trial. Exploring other lesion specifications, bone properties, and load application methods can form a more comprehensive method of predicting the mechanical behavior of the femur. This could be a significant tool to aid in making critical treatment decisions for efficient patient care.

Osteolytic lesions are formed when metastatic cancer spreads to the bone and causes tissue to decay. This can increase the risk of pathological fractures, which are caused by the weakening of bone due to conditions like cancer (1). Fracture fixation is a major procedure that physicians consider in the event bone metastases occur. Lesions can be detected using computed tomography (CT) scans and radiographs, but the visualizations captured cannot consistently determine if a bone's mechanical integrity has been compromised. Thus, it is difficult to determine if an invasive and costly procedure is needed to reduce the risk of fractures.

This study simulates the fracture process of a femur that incorporates bone lesions with different sizes and locations. This study's purpose is to give medical professionals a systematic approach to determining if a femur with lesions should be operated on.

The simulations in this study were performed on Finite Element (FE) Models of a femur that was imaged using Magnetic Resonance Imaging (MRI). Using Simpleware ScanIP, 10 different models were created (Figure 1). Each model was segmented into the femoral head and shaft regions to assign specific properties to each location. Lesions are commonly found in the femoral head, femoral neck, and greater trochanter, so three models containing lesions with diameters 10, 20, and 30 mm respectively were made for each location (2). Lesions within each location were centered around the same point in the model, which was found using the measure tool and created by deleting a sphere with the desired parameters from a mask of the entire bone. The tenth model was segmented, but it contained no lesions and served as the control group for comparison.

FE simulations were run using the 3D-generated FE models in Abaqus using homogenous material properties. Young's Modulus values of 1.3×10^{10} and 1.85×10^{10} Pascals were assigned to the head and shaft regions respectively, and the Poison's Ratio was 0.3 for both regions. The head region where fractures most commonly occur was assigned a Maximum Principal Stress (MAXPS - the threshold value of stress before damage begins to develop) of 104 MPa, and Damage Evolution Fracture Energy of 1.16 kj/m^2 (3, 4). A reference point was selected as the location to apply a displacement load, which was applied by coupling the point to a section of nodes on the surface of the femoral head. The load used on each model mimicked a stance position with a resultant 4.1 mm load at ~7° from the vertical (5). Future trials will explore different load applications in addition to expanding on incorporating an improved quantity and quality of models.

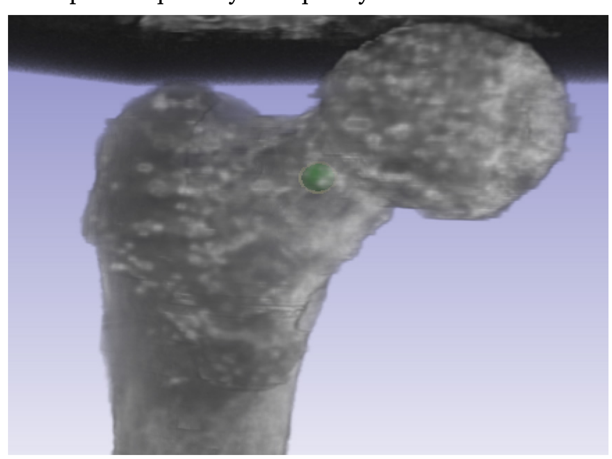

Figure 1. Image of a 3-Dimensional model developed in ScanIP with a 10 mm lesion in the femoral neck. The location and size of the lesion are represented by the green sphere in the center of the image.

In every simulation, with and without lesions, the crack fully initiated in the proximal neck of the femur. The fracture load decreased with lesion size and showed variability among lesion locations (Figure 2).

This supports the idea that the mechanical integrity of a femur becomes increasingly compromised by larger metastases. The data suggests that the most critical location is the neck, as this is consistently where the smallest amount of force was required to initiate a crack. The reaction force was extracted from each step and paired with the increment at which the crack was first initiated, and a reaction force vs. displacement graph was plotted for each simulation in which the slope was derived to find the stiffness in N/mm (Figure 3). The parameters used in this study simulate the variability seen in clinical cases. Replicating this systemic approach with other lesion specifications, bone properties, and load application methods can be used to predict the patient-specific mechanical behavior of femurs. Furthering these computational simulations can assist medical professionals in assessing fracture risk, aiding in making critical treatment decisions. Using these results, costly, invasive surgeries can be avoided, and more efficient patient care can be provided.

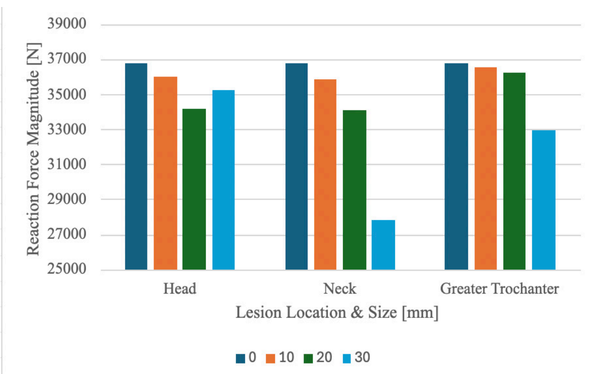

Figure 2. Force Required for Crack Propagation. Graph showing force required for the fracture propagation of femurs with each lesion size and location. Each column in Figure 2 displays the force required for a crack to propagate in the specified location and size of a lesion in the given model. The demonstrated trend is that the mechanical integrity of the bone decreases as the lesion size increases, with the most drastic decrease in strength taking place when the lesion is found in the neck.

Location	Size [mm]	Stiffness [N/mm]	RF at Crack Formation [N]
Head	10	21007	3.60E+04
	20	20350	3.42E+04
	30	20184	3.52E+04
Neck	10	21317	3.58E+04
	20	20372	3.41E+04
	30	20611	2.78E+04
Greater Trochanter	10	21494	3.65E+04
	20	21153	36185.9
	30	19424	32929.3
NO LESIONS:		20934	36747.9

Figure 3. Stiffness and Reaction Force at each Crack. The simulations performed on each model recorded the corresponding reaction forces to the progressive displacement loads. Using the Status Extended Finite Element Modeling (STATUSXFEM) and Phase-Field Level Set Method (PHILSM) output variables, the specific reaction force required for crack formation was detected. Since the unit for stiffness is Newtons/millimeters, this data also provided information about the stiffness of each model by dividing the reaction force by its respective displacement load. Similarly to the decrease in amount of force it takes to crack the femur, the stiffness generally decreases as the lesion size increases in each region.

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REFERENCES

1. Rajapakse, C. S., Gupta, N., Evans, M., Alizai, H., Shukurova, M., Hong, A. L., Cruickshank, N. J., Tejwani, N., Egol, K., Honig, S.,Chang, G., Influence on bone lesion location on femoral bone strength assessed by MRI-based finite element modeling. *Bone*, 209, 209-217
2. Başdelioğlu, K. (2021, March 1). Bone metastasis: Evaluation of 1100 patients with breast cancer. *International journal of clinical and experimental pathology*. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7994145/
3. Demirtas, A., Rajapakse, C. S., Ural, A., Assessment of the multifactorial causes of atypical femoral fractures using a novel multiscale finite element approach. *Bone*, 135 (2020) 115318.
4. Gustafsson, A., Tognini, M., Bengtsson, F., Gasser, T.C., Isaksson, H., Grassi, L., Subject-specific FE models of the human femur predict fracture path and bone strength under single-leg-stance loading. *Journal of the Mechanical Behavior of Biomedical Materials* (2020) 1751-6161
5. Sternheim, A., Giladi, O., Gortzak, Y., Drexler, M., Salai, M., Trabelsi, N., Milgrom, C., & Yosibash, Z. (2018). Pathological fracture risk assessment in patients with femoral metastases using CT-based finite element methods. A retrospective clinical study. *Bone*, 110, 215–220. https://doi.org/10.1016/j.bone.2018.02.011

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