MRI-Based Radiomic Features Can Detect Femoral Component Loosening in Patients with Total Hip Arthroplasty

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Introduction: Total hip arthroplasty (THA) is an effective treatment for end-stage degenerative joint disease. With the number of primary THA procedures increasing to over one million annually in the US by 2040, a concomitant increase is anticipated in the number of revision surgeries [1,2]. Infection, mechanical complications, instability, and loosening are the most common reasons for THA revision surgery [3,4]. Radiography is the current standard for assessment of implant integration [5,6], however, loosening can go undetected due to the poor conspicuity of the soft-tissue fibrous membrane at the bone-implant interface [7,8]. In contrast, multi-spectral magnetic resonance imaging (MSI-MRI) enables high-resolution imaging near metallic implants with reduced susceptibility artifacts [9,10] and displays high sensitivity (75%) and specificity (100%) for detecting of femoral component loosening [11]. Radiomics, or image texture features, may be able to improve the sensitivity of MSI-MRI detection of femoral loosening by providing quantitative assessments of how signal intensity changes within the periprosthetic bone of loose implants. This study developed a radiomic classification model using texture features extracted from the femoral trabecular bone within MSI-MRI images of symptomatic patients with confirmed implant loosening and asymptomatic patients with no postoperative complications. We hypothesized that MSI-MRI-based radiomics would be capable of classifying loose from non-loose implants.

Methods: Following IRB approval with informed consent, symptomatic patients undergoing revision surgery underwent an MRI scan prior to surgery and femoral loosening was confirmed. A second cohort of asymptomatic primary THA patients received MRIs. All scanning was performed on clinical 1.5T scanners (GE Healthcare). Morphologic [12] and MSI-MRI [9] images were acquired. The trabecular compartment was manually segmented from the MSI-MRI images and subdivided into Gruen zones [13]. Analysis was limited to the four proximal zones (1, 7, 8, and 14) and a combined "full" proximal region. Two-dimensional overlapping patches of sizes: [12x12, 24x24, 36x36, 48x48, 56x56, 64x64] mm^2 were extracted. Patches were grouped by Gruen zone or full proximal region. A total of 96 radiomic features were computed per patch using PyRadiomics [14]. Cross-validated logistic regression with L2 regularization was implemented [15] to evaluate radiomic feature classification of loose implants. For each patch size and region of interest (zones or full), z-score normalization was applied to the extracted radiomic features. Feature space was reduced through principal component analysis while maintaining 95% of explained variance. The optimal hyperparameters, including regularization strength, were tuned via stratified five-fold cross-validation. Class-balanced 5-fold cross-validation evaluated the optimal model's performance while maintaining strict independence between training and test sets. Model performance was assessed using the mean area under the receiver-operating characteristic curve (AUC) across folds.

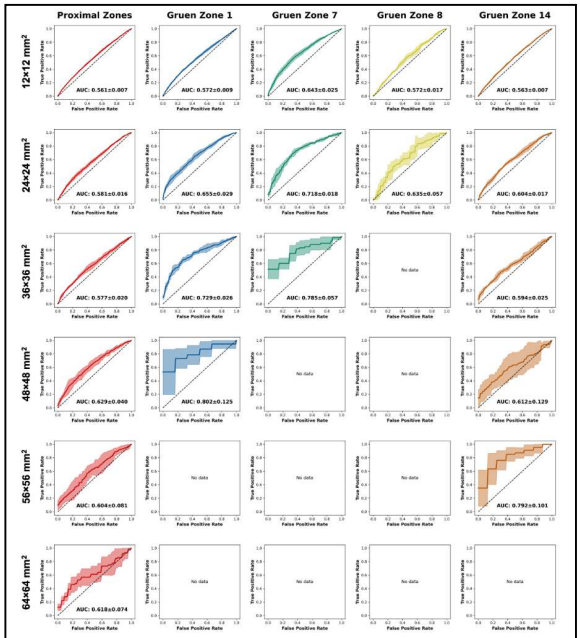

Figure 1. Receiver operator characteristic curves by full proximal femur or individual Gruen zones (columns) and by patch size (rows). Mean ROC curve is plotted (bold line) with the 95% confidence interval (shaded area). In general, an improvement of classification performance, via the area under the curve (AUC), was found for the individual Gruen zones with increasing patch size.

Results: Image data from 40 asymptomatic (Age: 64.2 ± 9.8 years [mean±SD], Length of Implantation [LOI]: 3.7 ± 3.3 years, 20 male) and 36 symptomatic patients with confirmed femoral loosening (Age: 67.0 ± 10.1 years, LOI: 10.2 ± 10.3 years, 18 male) were evaluated. Zonal radiomic classification of loosening improved with increasing patch size, reaching a maximum AUC of 0.79 in Gruen zones 1 (lateral), 7 (medial), and 14 (posterior) at the largest available patch sizes. Full proximal models reached a maximum AUC of 0.63 with 48x48 mm^2 patches.

Discussion: This preliminary investigation demonstrated that MSI-MRI-based radiomics can accurately detect femoral component loosening in patients with THA, offering a quantitative adjunct to the current qualitative assessment of implant integration. In reaching a maximum AUC of 0.79, zonal radiomic models achieve similar sensitivity to expert interpretation of MSI-MRI [11], indicating radiomics could improve diagnostic confidence in loosening detection, particularly in settings with radiologists less experienced in musculoskeletal imaging. Improved performance of zonal models highlight the anatomical specificity of loosening. Medial-anterior implantation of the femoral stem leads to asymmetric stress distribution and trabecular remodeling [16,17], potentially creating greater signal variation between Gruen zones. Migration of the implant stem, as often occurs for loose implants, further exaggerates these changes, and is likely detected by radiomics. This study had several limitations. First, patch extraction was constrained by available bone, particularly limiting model creation in Gruen zone 8 (anterior). Second, we utilized square patches whereas vertically oriented patches aligned with femoral anatomy may have permitted more data available for analysis. Third, MSI-MRI greatly resolves susceptibility artifacts, however, subtle artifacts may still be present [18] and may have influence the results. Fourth, acetabular component loosening was not evaluated, as segmentation of the acetabular trabecular compartment was more challenging than that of the femur. Fifth, although balanced, a limited cohort of 76 patients may inhibit current model generalizability. Finally, the relationship between loosening and specific implant manufacturers or prosthesis design were not evaluated. In summary, the current investigation provides a feasible method of quantitatively evaluating qualitative assessments of implant integration. Models generated using larger datasets could aid in earlier detection of loosening, enhancing post-operative care choices and improving patient mobility.

Clinical Relevance: This study demonstrates that MSI-MRI based radiomic features can classify the qualitative diagnosis of implant loosening in patients with THA. The findings provide a foundation for future radiomic tools to assist in early, quantitative detection of aseptic loosening during routine clinical imaging.

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