The Prognostic Value of Preoperative MRI Radiomics for Patient-Reported Outcomes of ACL Reconstruction

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INTRODUCTION: Outcomes vary considerably following anterior cruciate ligament reconstruction (ACLR) despite standardization of surgical techniques and rehabilitation. One-year patient-reported outcome measures (PROMs) offer a patient-centered, clinically-interpretable assessment of functional recovery and symptom state. PROMs remain difficult to predict using demographics, surgical variables, or baseline PROM instruments alone. Preoperative MRI is standardly obtained to diagnose and inform management of ACL injury, yet the prognostic value of data from this routine imaging remains poorly defined with respect to PROMs. Radiomics enables high-throughput quantification of shape and intensity features from MRI sequences and may reveal morphologic markers of recovery potential or risk for subsequent degenerative changes. We aimed to investigate whether radiomic features from routine preoperative imaging are associated with PROMs at 1 year following ACLR and if they enhance the prediction of outcomes beyond preoperative or operative data alone.

METHODS: All human subject data collection and analyses were performed in compliance with institutional review board approved protocols. Subjects were identified from a prospective outcomes registry capturing baseline demographic, clinical/operative variables, and longitudinal PROMs for patients who underwent ACLR at a large multisite academic health system between 2015 and 2022. PROMs included the following validated instruments captured at baseline and 1 year (T1) after ACLR: KOOS subscores, VR-12 physical and mental component scores, and the HSS Pedi-FABS athletic activities score. Patient acceptable symptom state (PASS) and return-to-work (RTW) status were also assessed at 1 year. Subjects with both T1 PROMs and preoperative sagittal proton density fat-suppressed fast spin-echo knee MRI available were included. Images were automatically segmented using a previously validated in-house deep-learning model, generating masks for 4 cartilage regions and both menisci. A range of 3D shape, first-order grayscale intensity, and higher-order texture features were quantified in each segmented region using the open-source PyRadiomics python package and in-house scripts were used for extracting additional shape descriptors. Univariate associations between each radiomic feature were investigated with statistical testing adjusted for multiple comparisons (Benjamini-Hochberg FDR) and reported as the number of significantly associated features per knee region for each PROM. Prior to predictive modeling, the dataset was randomly split 80:20 into training and test sets. Variables with near-zero variance or high collinearity were removed before feature selection per outcome using regularized linear regression (LASSO), retaining features with non-zero coefficients. Five modeling conditions were evaluated: (A) preoperative clinical variables only, (B) preoperative + intraoperative variables, (C) radiomics only, (D) radiomics + preoperative variables, and (E) radiomics + preoperative + intraoperative variables. Random forest regressors or classifiers were constructed for each outcome using predictor sets from each modeling condition. Models were evaluated using the held-out test set and assessed with RMSE (regressors) or ROC AUC (classifiers).

RESULTS: Over 3000 radiomic features were extracted from images for 1108 patients (56% female) for which T1 PROMs were available. Univariate analysis revealed statistically significant radiomics-PROM associations (FDR-corrected $p < 0.05$) for 5/9 outcomes (KOOS PS, HSS Pedi-FABS, VR-12 PCS + MCS, and RTW) with a maximum univariate effect size of ≈ 0.2 and a concentration of significantly associated features in the patellar cartilage (Figure 1). However, when predicting outcomes, the addition of radiomic data to preoperative and operative variables offered only modest decrease in RMSE for KOOS pain score prediction only (reduction of 0.1-0.2 RMSE units). For remaining continuous PROMs (other KOOS subscores, VR-12, HSS Ped-FABS), radiomic features did not meaningfully reduce error (Table 1). Within models, radiomic features demonstrated lower relative importance, but ranked above some demographic and operative variables in select cases. Among binary outcomes, radiomic features modestly improved classification performance for PASS as evidenced by mild increase in AUC (Figure 2). Radiomic features alone demonstrated equivalent PASS classification performance (AUC) as baseline non-imaging data alone. RTW prediction was unchanged by radiomics data.

DISCUSSION: Radiomic data from standard preoperative knee MRI demonstrates statistically significant associations of modest magnitude with patient-reported functional and symptomatic outcomes 1 year following ACL reconstruction. The more frequent regional association with patellar features is consistent with known associations between patellofemoral degeneration and pain symptoms in post-traumatic osteoarthritis. However, on multivariate predictive modeling, radiomic data offers minimal additive predictive value compared to baseline clinical and operative features, likely reflecting multifactorial and non-structural determinants of these subjective outcomes. The small improvements in KOOS P and PASS prediction may suggest structural variation in cartilage or meniscal regions contributive to future pain perception, though these may reflect little to no true clinical value compared to baseline pain assessment. It remains difficult to identify clinical or imaging factors that offer substantial predictive value beyond baseline PROM scores. Radiomics performance was likely limited by scanner heterogeneity and anisotropic voxel resampling--limitations inherent to clinical MRI and a known tradeoff to the generalizability in non-research imaging.

SIGNIFICANCE: Radiomics provides a scalable automated approach for incorporating imaging biomarkers into prognostic modeling for ACLR. This study demonstrates a small association between routine baseline imaging data and 1-year patient-reported outcomes. Predictive value could possibly be improved with additional morphologic features to provide stronger personalized outcome prediction and inform patient counseling.

IMAGES AND TABLES:

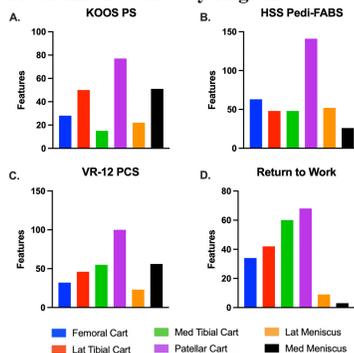**Figure 1. Significantly Associated Radiomic Features by Region**

Table 1. Model RMSE by Predictor Set

Outcome	Pre-op Only	Pre-op + Intra-op	Radiomics Only	Radiomics + Pre-op	Radiomics + Pre-op + Intra-op
KOOS PS	12.74	12.73	14.50	12.96	13.01
KOOS P	12.85	12.97	14.02	**12.68**	**12.82**
KOOS Q	21.93	22.18	23.28	22.11	22.28
KOOS JR	13.55	13.67	14.87	13.82	13.72
Pedi-FABS	6.91	6.92	8.00	7.15	6.92
VR-12 PCS	7.52	7.54	8.21	7.58	7.53
VR-12 MCS	8.01	8.05	9.59	8.21	8.23

Figure 2. PASS Classifier ROC