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# Preoperative factors predict prolonged length of stay, serious adverse complications, and readmission following operative intervention of proximal humerus fractures: a machine learning analysis of a national database

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**Background:** Proximal humerus fractures are a common injury, predominantly affecting older adults. This study aimed to develop risk-prediction models for prolonged length of hospital stay (LOS), serious adverse complications, and readmission within 30 days of surgically treated proximal humerus fractures using machine learning (ML) techniques.

**Methods:** Adult patients (age >18) who underwent open reduction internal fixation (ORIF), hemiarthroplasty, or total shoulder arthroplasty for proximal humerus fracture between 2016 and 2021 were included. Preoperative demographic and clinical variables were collected for all patients and used to establish ML-based algorithms. The model with optimal performance was selected according to area under the curve (AUC) on the receiver operating curve (ROC) curve and overall accuracy, and the specific predictive features most important to model derivation were identified.

**Results:** A total of 7473 patients were included (72.1% male, mean age 66.2 ± 13.7 years). Models produced via gradient boosting performed best for predicting prolonged LOS and complications. The model predicting prolonged LOS demonstrated good discrimination and performance, as indicated by (Mean: 0.700, SE: 0.017), recall (Mean: 0.551, SE: 0.017), accuracy (Mean: 0.717, SE: 0.010), F1-score (Mean: 0.616, SE: 0.014), AUC (Mean: 0.779, SE: 0.010), and Brier score (Mean: 0.283, SE: 0.010) Preoperative hematocrit, preoperative platelet count, and patient age were considered the strongest predictive features. The model predicting serious adverse complications exhibited comparable discrimination [precision (Mean: 0.226, SE: 0.024), recall (Mean: 0.697, SE: 0.048), accuracy (Mean: 0.811, SE: 0.010), F1-score (Mean: 0.341, SE: 0.031)] and superior performance relative to the LOS model [AUC (Mean: 0.806, SE: 0.024), Brier score (Mean: 0.189, SE: 0.010), noting preoperative hematocrit, operative time, and patient age to be most influential. However, the 30-day readmission model achieved the weakest relative performance, displaying low measures of precision (Mean: 0.070, SE: 0.012) and recall (Mean: 0.389, SE: 0.053), despite good accuracy (Mean: 0.791, SE: 0.009).

**Conclusion:** Predictive models constructed using ML techniques demonstrated favorable discrimination and satisfactory-to-excellent performance in forecasting prolonged LOS and serious adverse complications occurring within 30 days of surgical intervention for proximal humerus fracture. Modifiable preoperative factors such as hematocrit and platelet count were identified as significant predictive features, suggesting that clinicians could address these factors during preoperative patient optimization to enhance outcomes. Overall, these findings highlight the potential for ML techniques to enhance preoperative management, facilitate shared decision-making, and enable more effective and personalized orthopedic care by exploring alternative approaches to risk stratification.

This study was determined to be exempt prior to initiation.

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Proximal humerus fractures are a common injury, accounting for approximately 4%-5% of all fractures. Incidence follows a bimodal distribution, though the majority of injuries occur in older adults via low-energy mechanisms.[14,39] Effective management may range from nonoperative treatment with a sling or hanging arm cast for nondisplaced fractures to surgical intervention for more severe cases; however, optimal treatment strategies for this fracture type remain a topic of much debate.[34,41,43] A recent systematic review of 92 studies and 4500 patient determined open reduction internal fixation (ORIF) achieved superior clinical outcomes compared to hemiarthroplasty and reverse total shoulder arthroplasty according to measures of American Shoulder and Elbow Surgeons score (ASES), Disabilities of the Arm, Shoulder, and Hand score (DASH), and Constant score, despite a significantly higher rate of reoperation.[18] In addition to mode of treatment,[19] numerous other factors have been suggested to influence risk for complication and adverse outcomes following proximal humerus fracture, including patient age,[46] sex,[25] comorbidities,[7,8] and fracture severity.[19,47] Older patients and those with multiple comorbidities may experience relatively longer hospital stays due to slower recovery times and increased risk of complications.[10,25] Patients with more severe fractures may also require longer hospitalization to manage pain and achieve adequate functional recovery.[19] Considering the incidence of proximal humerus fracture is projected to rise by 300% between 2000 and 2030, amounting to approximately 275,000 fractures per annum by 2030,[29] it is crucial for health-care providers to identify patients at increased risk for complications and develop personalized treatment plans that reduce the likelihood of adverse outcomes.

Several prior studies have sought to predict risk for complication, adverse outcomes, and reoperation following operative management of proximal humerus fracture.[1,15,35,40,49,52] For example, Petrigliano and colleagues showed risk for short-term complication to be significantly greater for patients over age 65, male patients, those with comorbidities, and those living in an area with an income in the lowest two quintiles.[40] Modifiable risk factors such as hypoalbuminemia have also been identified, suggesting additional measures may be taken during preoperative patient optimization to minimize risk.[49] However, current universal and procedure-specific models for predicting risk following surgical intervention for proximal humerus fracture have limitations, such as lack of transparency and insufficient external validation to establish performance across diverse settings.[20] To address these, there has been a growing body of research investigating applications of machine learning (ML) for predicting outcomes and developing treatment plans.[7,12,31] ML is a form of artificial intelligence in which algorithms and statistical models continuously learn and improve by identifying patterns and complex relationships in large data sets with the ultimate goal of making decisions with minimal human intervention.[24,31] Predictive models developed using ML techniques have already demonstrated clinical utility across several medical settings, including orthopedics[6,42]; however, no studies to date have leveraged ML to predict outcomes following operative treatment of proximal humerus fracture.

The current study therefore aimed to utilize ML methods and an extensive national database to develop and validate risk-prediction models for a prolonged length of hospital stay (LOS), severe adverse complications, and readmission within 30 days of proximal humerus fracture surgery.

## Methods

### *Study design and patient population*

The study population included adult patients (age >18 years) who presented to one of the participating American College of Surgeons-National Surgical Quality Improvement Program hospitals with proximal humerus fracture and underwent ORIF, hemiarthroplasty, or total shoulder arthroplasty between 2016 and 2021. Patients were identified through the following Current Procedural Terminology (CPT) codes 23615, 23616, 23630, 23670, 23680, 23470, and 23472 (Table I). Patients undergoing operative intervention for arthropathies, rotator cuff tears, malignancies, etc. were excluded.[33] Institutional Review Board exemption was obtained from Rush University Medical Center prior to study initiation given its use of publicly available deidentified data. The design and reporting of this study are in compliance with the Transparent Reporting of a Multivariable Prediction Model for Individual Prognosis or Diagnosis guidelines and the Journal of Medical Internet Research Guidelines for Developing and Reporting Machine Learning Predictive Models in Biomedical Research.[8,32]

### *Data preprocessing*

For features with <20% of data missing, imputation of categorical and continuous variables was calculated using the variable mode and variable mean strategies, respectively. Features for which > 20% of data was missing were excluded from model development. In total 28 features were included for model development.

### *Outcome and candidate predictive features*

Target outcomes included incidence of major complication (deep wound infection, dehiscence, pneumothorax, reintubation, pulmonary embolism, failed wean of intubation, renal insufficiency, renal failure, central nervous system-cerebrovascular accident, cardiac arrest, myocardial infarction, bleed, deep venous thrombosis, sepsis, or septic shock), prolonged LOS (≥2 days), and readmission within 30 days of surgery. The duration of ≥2 days for prolonged LOS was determined based off of the manuscript by Lopez et al in 2022 which noted mean hospital LOS was 1.7 days in patients treated with TSA for a variety of reasons (including proximal fracture).[31]

Preoperative demographic factors (sex, race, age, body mass index (BMI), American Society of Anesthesiologists (ASA) class, operation year, smoking status, financial status etc.), past medical history (diabetes, chronic obstructive pulmonary disease (COPD), congestive heart failure, renal failure, steroid use, bleeding disorders, past transfusion, and hypertension requiring medication) and clinical variables (preoperative sodium, blood urea nitrogen (BUN), creatinine, albumin, bilirubin, Serum Glutamic-Oxaloacetic Transaminase, alkaline phosphatase, white blood cell (WBC) count, hematocrit, platelets, Partial Thromboplastin Time, prothrombin time, and international normalized ratio (INR)) were collected to serve as predictive features in model development.

**Table I**
Included CPT codes.

| Code | Description |
|---|---|
| 23615 | Open treatment of proximal humeral (surgical or anatomical neck) fracture, includes internal fixation, when performed, includes repair of tuberosity(s), when performed |
| 23616 | Open treatment of proximal humeral (surgical or anatomical neck) fracture, includes internal fixation, when performed, includes repair of tuberosity(s), when performed; with proximal humeral prosthetic replacement |
| 23630 | Open treatment of greater humeral tuberosity fracture, includes internal fixation, when performed |
| 23670 | Open treatment of shoulder dislocation, with fracture of greater humeral tuberosity, includes internal fixation, when performed |
| 23680 | Open treatment of shoulder dislocation, with surgical or anatomical neck fracture, includes internal fixation, when performed |
| 23470 | Arthroplasty, glenohumeral joint; hemiarthroplasty |
| 23472 | Arthroplasty, glenohumeral joint; total shoulder |

*CPT*, current procedural terminology.

### *Statistical analyses, predictive modeling, and validation*

Demographic and clinical information was analyzed using R (RStudio, PBC, Boston, MA). Specifically, differences between patients who did and did not experience prolonged LOS, serious adverse outcome, and readmission within 30 days of surgical treatment for proximal humerus fracture were assessed using chi-square and t-test for categorical and continuous variables, respectively. Data are reported as frequencies and percentages for categorical variables and mean ± standard deviation for continuous variables. $P$ values $\leq$ .05 were considered statistically significant.

Programming for ML model development was performed using Python version 3.11.2 (Python Software Foundation, Wilmington, DE, USA). Models for prediction of each outcome (e.g., major complication, prolonged LOS, 30-day readmission) were generated using support vector machine, random forest, logistic regression, gradient boosting, and extreme gradient boosting (XGboost) techniques. Full description of each of these models is outside the scope of this; however, the manuscript by Shah et al 2022 provides an in depth review of each of the included models.[44] Classification of the target outcomes that were not balanced was oversampled (upsampled) from the minority class for optimal model training using the Synthetic Minority Oversampling Technique.[5] Patients were randomized into training (70%) or testing (30%) cohorts. Specifically, the training cohort was used to develop the model and allow the program to determine the optimal predictive algorithm from the provided data, which was subsequently applied to the testing cohort to validate the model's predictive efficacy. The algorithms were constructed on a training set of patients (70% of initial cohort) using fivefold cross-validation.

The best-performing model was selected according to the area under the curve (AUC) on the receiver operating curve (ROC) and model accuracy. Additional model performance metrics, including precision, recall, F1-score, and Brier score, were also evaluated. Moreover, the calibration for each model was visually summarized. F1 score represents a measure of the harmonic mean of model precision and recall, with a perfect score of 1.0.[30] Brier score serves as an additional measure of overall model performance, with a score of 0 representing a perfect model and a score of 1 signifying poorest prediction. Each model was also assessed for the features that were most important to the derivation of the selected model. Specifically, each variable's usefulness in helping the model to predict the target outcome was calculated as the improvement in model performance attributable to each split point in a single decision tree weighted by the number of observations for which the node was responsible.[21] Further information regarding each of the utilized metrics can be found in a comprehensive manuscript by Polce et al 2022.[41]

## Results

Overall, a total of 7473 patients with proximal humerus fracture were included in this study (72.1% female, mean age 66.2 ± 13.7 years). A summary of baseline demographics, medical comorbidities, and preoperative labs can be found in Table II.

### *Prolonged length of stay*

Patients who required a prolonged LOS were more likely to be female (odds ratio [OR] 1.1, 95% confidence interval [CI] 1.0-1.2; $P = .046$), to be nonwhite (OR 1.3, 95% CI 1.2-1.4; $P < .001$) and to have an ASA class $\geq$ 3 (OR 2.5, 95% CI 2.3-2.8; $P < .001$); however, they were less likely to be smokers (OR 0.86, 95% CI 0.76-0.97; $P = .016$) or to be functionally independent (OR 2.8, 95% CI 2.3-3.5; $P < .001$) (Table III). Patients requiring prolonged LOS were older (69.1 years ± 13.2 vs. 62.4 years ± 13.4; $P < .001$) and exhibited higher rates of diabetes (OR 1.6, 95% CI 1.4-1.7; $P < .001$), COPD (OR 1.7, 95% CI 1.5-2.1; $P < .001$), congestive heart failure (OR 4.0, 95% CI 2.5-6.2; $P < .001$), hypertension requiring medication (OR 1.6, 95% CI 1.5-1.8; $P < .001$), dialysis (OR 7.2, 95% CI 2.5-21.3; $P < .001$), steroid use (OR 1.6, 95% CI 1.2-2.0; $P < .001$), bleeding disorder(s) (OR 3.1, 95% CI 2.5-4.1; $P < .001$), history of transfusion (OR 22.8, 95% CI 9.2-56.4; $P < .001$), and preoperative sepsis (OR 4.6, 95% CI 3.5-6.2; $P < .001$). Multiple preoperative lab differences were present among patients requiring prolonged LOS, including lower sodium (137.5 ± 3.6 vs. 138.3 ± 3.3; $P < .001$), lower albumin (3.7 ± 0.6 vs. 3.9 ± 0.5; $P < .001$), lower hematocrit (35.4 ± 5.3 vs. 38.0 ± 4.7; $P < .001$), and lower platelets (246.2 ± 92.8 vs. 272.1 ± 87.0; $P < .001$), as well as higher BUN (18.3 ± 10.0 vs. 16.6 ± 7.8; $P < .001$), higher bilirubin (0.7 ± 0.7 vs. 0.7 ± 0.6; $P = .010$), higher Serum Glutamic-Oxaloacetic Transaminase (34.2 ± 41.2 vs. 30.8 ± 39.0; $P = .013$), higher WBC (9.0 ± 3.4 vs. 8.6 ± 3.0; $P < .001$), and higher INR (1.1 ± 0.2 vs. 1.0 ± 0.2; $P < .001$). Moreover, those with prolonged LOS experienced longer operative times (125.7 minutes ± 59.0 vs. 112.3 minutes ± 51.0; $P < .001$) and greater lengths of stay (4.6 days ± 4.8 vs. 0.5 days ± 0.5; $P < .001$) than those discharged within 2 days of surgery. Patients undergoing open treatment of proximal humeral (surgical or anatomical neck) fracture (56.73%; 119/210), total shoulder arthroplasty (glenoid and proximal humeral replacement (e.g., total shoulder)) (53.4%; 1231/2305), and hemiarthroplasty (49.8%; 168/337), indicated by CPT codes 23616, 23472, and 23470, respectively, demonstrated highest rates of prolonged LOS (Table IV).

### *Serious adverse complications*

Patients who experienced a serious adverse event within 30 days of surgery were older (72.0 years ± 12.5 vs. 64.7 years ± 13.6; $P < .001$) and more likely to have an ASA class $\geq$ 3 (OR 3.4, 95% CI 2.7-4.2; $P < .001$) than those without postoperative complication. They were also less likely to be functionally independent at baseline (OR 2.4, 95% CI 1.8-3.2; $P < .001$) and had lower BMIs (28.5 ± 7.2 vs. 29.8 ± 7.4; $P < .001$) than their counterparts (Table V). The serious adverse event group also displayed several preoperative lab differences, including lower sodium (137.1 ± 4.0 vs. 138.0 ± 3.4; $P < .001$), lower albumin (3.5 ± 0.6 vs. 3.8 ± 0.5; $P < .001$), lower hematocrit (31.8 ± 5.7 vs. 37.2 ± 4.9; $P < .001$), lower platelets (239.0 ± 111.6 vs. 261.8 ± 88.4; $P < .001$), higher BUN (21.6 ± 12.8 vs. 17.0 ± 8.5; $P < .001$), higher creatinine (1.1 ± 0.8 vs. 0.9 ± 0.4; $P = .015$), higher bilirubin (0.7 ± 0.7 vs. 0.7 ± 0.6; $P = .022$), and

**Table II**
Population demographics, comorbidities, and preoperative labs.

| Demographics | Count (%) |
|---|---|
| Sex (F) | 5583 (74.7%) |
| Race (White) | 5875 (78.6%) |
| Age | 65.18 ± 13.69 |
| BMI | 29.68 ± 7.39 |
| Diabetes (YES) | 1552 (20.4%) |
| Smoker (YES) | 1348 (18.0%) |
| Functionally independent (YES) | 7057 (94.4%) |
| ASA class (1 - no disturb) | 325 (4.4%) |
| COPD (YES) | 447 (6.0%) |
| CHF (YES) | 96 (1.3%) |
| Hypertension on medication (YES) | 3959 (53.0%) |
| Dialysis (YES) | 24 (0.3%) |
| Steroid (YES) | 264 (3.5%) |
| Bleeding disorder (YES) | 282 (3.8%) |
| Transfusion (YES) | 82 (1.1%) |
| **Preoperative labs** | **Mean ± SD** |
| Sodium | 137.94 ± 3.48 |
| BUN | 17.41 ± 9.00 |
| Creatinine | 0.87 ± 0.43 |
| Albumin | 3.78 ± 0.53 |
| Bilirubin | 0.68 ± 0.63 |
| Serum Glutamic-Oxaloacetic Transaminase (SGOT) | 32.54 ± 40.20 |
| Alkaline phosphatase | 91.46 ± 45.45 |
| WBC | 8.82 ± 3.20 |
| Hematocrit | 36.75 ± 5.15 |
| Platelet count | 259.96 ± 90.7 |
| PTT | 28.98 ± 6.36 |
| INR | 117.79 ± 54.79 |
| PT | 2.16 ± 3.71 |

*BMI*, body mass index; *ASA*, American Society of Anesthesiologists; *COPD*, chronic obstructive pulmonary disease; *CHF*, congestive heart failure; *BUN*, blood urea nitrogen; *WBC*, white blood cell; *PTT*, partial thromboplastin time; *PT*, prothrombin time; *INR*, international normalized ratio; *SD*, standard deviation.

higher INR (1.1 ± 0.2 vs. 1.0 ± 0.2; $P < .001$). Moreover, patients with a serious adverse event also experienced longer operative times (138.3 ± 68.3 minutes vs. 116.3 ± 53.4 minutes; $P < .001$) and greater lengths of stay (5.3 ± 5.3 days vs. 1.9 ± 3.4 days; $P < .001$). Patients undergoing open treatment of proximal humeral (surgical or anatomical neck) fracture (10.5%; 22/210) and total shoulder arthroplasty (glenoid and proximal humeral replacement (e.g., total shoulder)) (10.1%; 234/2305), indicated by CPT codes 23616 and 23472, respectively, demonstrated highest rates of serious adverse complications (Table VI).

*Readmission*

Patients who were readmitted within 30 days of surgery tended to be older (69.3 years ± 14.0 vs. 65.0 years ± 13.7; $P < .001$) and were more likely to be male (OR 1.3, 95% CI 1.0-1.7; $P = .042$), less likely to be functionally independent (OR 2.9, 95% CI 2.0-4.2; $P < .001$), and more likely to have an ASA class $\geq$ 3 (OR 3.0, 95% CI 2.3-4.0; $P < .001$; Table VII). Furthermore, those with a readmission displayed higher rates of diabetes (OR 1.4, 95% CI 1.0-1.8; $P = .027$), COPD (OR 2.3, 95% CI 1.6-3.4; $P < .001$), hypertension requiring medication (OR 1.5, 95% CI 1.1-1.9; $P = .002$), and bleeding disorder (OR 2.0, 95% CI 1.2-3.2; $P = .004$), and they were also more likely to have required dialysis (OR 8.5, 95% CI 3.3-21.7; $P < .001$) or transfusion (OR 6.4, 95% CI 3.7-11.2; $P < .001$). Multiple preoperative differences were present in the readmission group, including lower sodium (137.2 ± 4.2 vs. 138.0 ± 3.4; $P = .002$), lower albumin (3.4 ± 0.6 vs. 3.8 ± 0.5; $P < .001$), lower hematocrit (33.9 ± 5.8 vs. 36.9 ± 5.1; $P < .001$), and lower platelets (250.6 ± 115.7 vs. 260.3 ± 89.3; $P = .005$), as well as higher alkaline phosphatase (107.5 ± 65.8 vs. 90.6 ± 44.0; $P < .001$) and higher Partial Thromboplastin Time (30.1 ± 5.5 vs. 28.9 ± 6.3; $P = .016$). Moreover, those readmitted within 30 days of surgery were more likely to have greater LOS following the index procedure (3.7 ± 4.1 days vs. 2.1 ± 3.7 days; $P < .001$).

*Model performance and feature importance*

*Prolonged length of stay*

The gradient boosting method produced the optimal model for predicting prolonged LOS, achieving good discrimination as measured by precision (Mean: 0.700, standard error [SE]: 0.017), recall (Mean: 0.551, SE: 0.017), accuracy (Mean: 0.717, SE: 0.010), and F1-score (Mean: 0.616, SE: 0.014). Overall model performance was also determined to be adequate, with AUC (Mean: 0.779, SE: 0.010) and Brier score (Mean: 0.283, SE: 0.010) (Figs. 1 and 2). Preoperative factors identified by the algorithm as most important for predicting prolonged LOS were preoperative hematocrit, preoperative platelet count, age, operative time, CPT code, preoperative WBC, ASA class, presence of preoperative sepsis, preoperative BUN, and preoperative sodium (Fig. 3, *A*).

*Serious adverse complications*

When predicting incidence of serious adverse complications, gradient boosting again generated the best-performing model, demonstrating comparable discrimination [precision (Mean: 0.226, SE: 0.024), recall (Mean: 0.697, SE: 0.048), accuracy (Mean: 0.811, SE: 0.010), F1-score (Mean: 0.341, SE: 0.031)] and superior performance relative to the LOS model [AUC (Mean: 0.806, SE: 0.024), Brier score (Mean: 0.189, SE: 0.010), Figs. 1 and 2]. Preoperative factors determined to be most important for predicting serious adverse complications were preoperative hematocrit, operative time, age, preoperative platelet count, BMI, preoperative BUN, CPT code, race, preoperative sodium, and preoperative WBC (Fig. 3, *B*).

*Readmission*

As with prediction of prolonged LOS and serious adverse complications, gradient boosting again produced the model with best performance in predicting incidence of readmission within 30 days of surgery. In contrast to those models, however, the 30-day readmission model performed poorly (AUC – Mean: 0.660, SE: 0.032; Brier score – Mean: 0.209, SE: 0.009), displaying low measures of precision (Mean: 0.070, SE: 0.012) and recall (Mean: 0.389, SE: 0.053) despite good accuracy (Mean: 0.791, SE: 0.009; Figs. 1 and 2). Preoperative factors identified as most important for predicting 30-day readmission were preoperative hematocrit, age, preoperative platelet count, operative time, BMI, ASA class, preoperative BUN, preoperative WBC, preoperative sodium, and preoperative creatinine (Fig. 3, *C*).

## Discussion

In this retrospective study, models for predicting prolonged LOS, serious adverse complications, and 30-day readmission following surgical treatment of proximal humerus fracture were developed and validated using ML approaches and leveraging a national, multicenter database. The ML algorithms incorporated various preoperative demographic and clinical parameters, yielding good discrimination and acceptable-to-excellent performance in predicting prolonged LOS and serious adverse complications within 30 days of surgery. Key features determined to be most predictive in both models included preoperative hematocrit, preoperative platelet count, patient age, and operative time. To the best of the authors' knowledge, this study is the first to develop algorithms specifically intended to predict prolonged LOS and serious adverse complications after proximal humerus fracture treatment.

**Table III**
Demographics prolonged LOS.

| | Short LOS (<2 d) (n = 4417) | Prolonged LOS (≥2 d) (n = 3056) | *P* value | 95% CI | | |
|---|---|---|---|---|---|---|
| | | | | Odds ratio | Lower limit | Upper limit |
| Sex (F) | 3263 (73.9%) | 2320 (75.9%) | **.046** | 1.11 | 1.00 | 1.24 |
| Race (White) | 3551 (80.4%) | 2324 (76.1%) | **<.001** | 1.29 | 1.16 | 1.44 |
| Diabetes (YES) | 768 (17.4%) | 754 (24.7%) | **<.001** | 1.56 | 1.39 | 1.75 |
| Smoker (YES) | 836 (18.9%) | 512 (16.8%) | **.016** | 0.86 | 0.76 | 0.97 |
| Functionally independent (YES) | 4271 (96.7%) | 2786 (91.2%) | **<.001** | 0.35 | 0.29 | 0.43 |
| ASA Class (>=3) | 260 (5.9%) | 65 (0.2%) | **<.001** | 2.55 | 2.31 | 2.81 |
| COPD (YES) | 205 (4.6%) | 242 (7.9%) | **<.001** | 1.77 | 1.46 | 2.14 |
| CHF (YES) | 26 (0.6%) | 70 (2.3%) | **<.001** | 3.96 | 2.52 | 6.23 |
| Hypertension on medication (YES) | 2116 (47.9%) | 1843 (60.3%) | **<.001** | 1.65 | 1.51 | 1.81 |
| Dialysis (YES) | 4 (0.1%) | 20 (0.6%) | **<.001** | 7.27 | 2.48 | 21.28 |
| Steroid (YES) | 127 (2.9%) | 137 (4.5%) | **<.001** | 1.59 | 1.24 | 2.03 |
| Bleeding disorder (YES) | 91 (2.1%) | 191 (6.3%) | **<.001** | 3.17 | 2.46 | 4.09 |
| Transfusion (YES) | 5 (0.1%) | 77 (2.5%) | **<.001** | 22.81 | 9.22 | 56.42 |
| Preoperative sepsis (YES) | 64 (1.4%) | 197 (6.4%) | **<.001** | 4.69 | 3.52 | 6.24 |
| Age | 62.46 ± 13.36 | 69.11 ± 13.19 | **<.001** | | | |
| BMI | 29.63 ± 7.14 | 29.75 ± 7.76 | .860 | | | |
| Sodium | 138.33 ± 3.34 | 137.51 ± 3.58 | **<.001** | | | |
| BUN | 16.60 ± 7.84 | 18.31 ± 10.03 | **<.001** | | | |
| Creatinine | 0.85 ± 0.33 | 0.90 ± 0.53 | .062 | | | |
| Albumin | 3.93 ± 0.47 | 3.65 ± 0.56 | **<.001** | | | |
| Bilirubin | 0.66 ± 0.56 | 0.71 ± 0.68 | **.010** | | | |
| Serum Glutamic-Oxaloacetic Transaminase (SGOT) | 30.80 ± 39.00 | 34.22 ± 41.24 | **.013** | | | |
| Alkaline phosphatase | 91.18 ± 43.07 | 91.73 ± 47.61 | .266 | | | |
| WBC | 8.62 ± 3.02 | 9.05 ± 3.38 | **<.001** | | | |
| Hematocrit | 37.95 ± 4.67 | 35.34 ± 5.33 | **<.001** | | | |
| Platelet count | 272.11 ± 86.99 | 246.29 ± 92.83 | **<.001** | | | |
| INR | 1.04 ± 0.18 | 1.07 ± 0.18 | **<.001** | | | |
| PTT | 28.63 ± 5.14 | 29.22 ± 7.08 | .179 | | | |
| Operative time | 112.32 ± 50.95 | 125.69 ± 59.03 | **<.001** | | | |
| Length of stay | 0.5 ± 0.5 | 4.6 ± 4.8 | **<.001** | | | |

*ASA*, American society of Anesthesiologists; *COPD*, chronic obstructive pulmonary disease; *CHF*, congestive heart failure; *BMI*, body mass index; *BUN*, blood urea nitrogen; *WBC*, white blood cell; *INR*, international normalized ratio; *PTT*, partial thromboplastin time; *LOS*, length of stay; *CI*, confidence interval.
Bold indicates *P* value <.05.

**Table IV**
Comparison of Prolonged LOS by CPT code.

| CPT | Prolonged stay | | Total | *P* |
|---|---|---|---|---|
| | No (N, (%)) | Yes (N, (%)) | | |
| 23470 | 169 (50.1%) | 168 (49.9%) | 337 | <.001 |
| 23472 | 1074 (46.6%) | 1231 (53.4%) | 2305 | |
| 23615 | 2539 (64.9%) | 1373 (35.1%) | 3912 | |
| 23616 | 91 (43.3%) | 119 (56.7%) | 210 | |
| 23630 | 427 (84.5%) | 78 (15.5%) | 505 | |
| 23670 | 62 (57.9%) | 45 (42.1%) | 107 | |
| 23680 | 55 (56.7%) | 42 (43.3%) | 97 | |

*LOS*, length of stay; *CPT*, current procedural terminology.

While there remains a paucity of research investigating associations between preoperative anemia, prolonged LOS, and risk for postoperative complications following operative management of proximal humerus fracture, previous studies have reported increased incidences of surgical complications such as blood loss requiring transfusion and mortality in the setting of anemia.[26,28,36,38,45] In the current study, the identification of hematocrit as the primary feature in both the prolonged LOS and serious adverse event predictive models aligns with preexisting literature, with several studies providing evidence for associations of preoperative hematocrit, hemoglobin, and anemia with prolonged LOS and complication after orthopedic procedures. For example, undetected anemia bears significant implications on the outcome of elective orthopedic surgical procedures, carrying increased risk for adverse effects such as postoperative infection, transfusion, and longer inpatient stay after total hip arthroplasty.[17,37] Moreover, in a study of total shoulder arthroplasty cases which included patients with proximal humerus fracture, Doan et al noted severity of anemia to correlate with average hospital LOS, rate of readmission, rate of reoperation, and incidence of both minor and major postoperative complications.[13] Similarly, in a study of 310,311 patients who underwent major surgical procedures, including various orthopedic surgeries, Wu et al confirmed that preoperative anemia, even when mild, is an independent risk factor for poorer postoperative outcomes.[51] The identification of low hematocrit as the most important factor in the predictive models developed by the current study has promising clinical implications, as hematocrit represents a modifiable risk factor which may be addressed during preoperative patient optimization, potentially resulting in fewer complications and shorter hospital stays.

Platelet count emerged as the second and fourth most significant predictive features in the prolonged LOS and serious adverse event models, respectively. Although research on the specific relationships between preoperative platelet count, prolonged LOS, and postoperative complications following proximal humerus fracture is scarce, recent studies have associated platelet count with a number of health outcomes not necessarily confined to thrombotic and hemostatic processes, including cardiovascular health,[48] cancer, and all-cause mortality.[4] Specifically, Bonaccio et al reported that lower platelet count was significantly related to increased risk of mortality (hazard ratio = 2.17; 95% CI, 1.55-3.05) compared to patients in the normal platelet range according to multivariable analysis.[4] Indeed, platelet count may serve as a proxy for nutritional status, as a randomized control trial by Hernáez et al has also suggested that a healthy diet (e.g., the Mediterranean diet) may impact overall platelet count compared to low-fat controls.[22] Platelets are known to contain a wide range of soluble and cell-associated immunomodulatory molecules which have the capacity to enhance immune responses and, under certain circumstances, inhibit them. Further research is necessary to better elucidate the role of platelet count in

**Table V**
Demographics serious adverse complications.

| | Absence of serious adverse complication (n = 4314) | Presence of serious adverse complication (n = 3159) | *P* value | 95% CI | | |
|---|---|---|---|---|---|---|
| | | | | Odds ratio | Lower limit | Upper limit |
| Sex (F) | 5197 (74.6%) | 386 (75.5%) | .655 | 0.95 | 0.77 | 1.18 |
| Race (Non-White) | 1486 (21.3%) | 112 (21.9%) | .76 | 0.97 | 0.78 | 1.2 |
| Diabetes (YES) | 365 (19.8%) | 146 (28.6%%) | **<.001** | 1.62 | 1.33 | 1.98 |
| Smoker (YES) | 421 (18.1%) | 90 (17.6%) | .795 | 0.97 | 0.77 | 1.23 |
| Functionally independent (YES) | 6605 (94.9%) | 452 (88.4%) | **<.001** | 2.42 | 1.8 | 3.23 |
| ASA class (>=3) | 3364 (52.3%) | 403 (78.9%) | **<.001** | 3.4 | 2.73 | 4.22 |
| COPD (YES) | 400 (5.7%) | 47 (9.2%) | **<.001** | 1.66 | 1.21 | 2.28 |
| CHF (YES) | 76 (1.1%) | 20 (3.9%) | **<.001** | 3.69 | 2.24 | 6.06 |
| Hypertension on medication (YES) | 3624 (52.1%) | 335 (65.6%) | **<.001** | 1.75 | 1.45 | 2.12 |
| Dialysis (YES) | 16 (0.2%) | 8 (1.6%) | **<.001** | 6.9 | 2.94 | 16.21 |
| Steroid (YES) | 238 (3.4%) | 26 (5.1%) | **.048** | 1.51 | 1.00 | 2.29 |
| Bleeding disorder (YES) | 227 (3.3%) | 55 (10.8%) | **<.001** | 3.58 | 2.63 | 4.88 |
| Transfusion (YES) | 50 (0.7%) | 32 (6.3%) | **<.001** | 9.24 | 5.87 | 14.53 |
| Preoperative sepsis (YES) | 221 (3.2%) | 40 (7.8%) | **<.001** | 2.59 | 1.83 | 3.67 |
| Age | 62.32 ± 13.32 | 69.08 ± 12.22 | **<.001** | | | |
| BMI | 29.63 ± 7.13 | 29.74 ± 7.74 | .778 | | | |
| Sodium | 138.33 ± 3.34 | 137.53 ± 3.57 | **<.001** | | | |
| BUN | 16.55 ± 7.70 | 18.30 ± 10.09 | **<.001** | | | |
| Creatinine | 0.84 ± 0.32 | 0.90 ± 0.53 | **.015** | | | |
| Albumin | 3.94 ± 0.46 | 3.65 ± 0.55 | **<.001** | | | |
| Bilirubin | 0.66 ± 0.58 | 0.71 ± 0.68 | **.022** | | | |
| Serum Glutamic-Oxaloacetic Transaminase (SGOT) | 30.93 ± 39.50 | 33.99 ± 40.77 | **.038** | | | |
| Alkaline phosphatase | 91.02 ± 43.26 | 91.86 ± 47.33 | .462 | | | |
| WBC | 8.61 ± 3.01 | 9.04 ± 3.38 | **<.001** | | | |
| Hematocrit | 38.00 ± 4.64 | 35.40 ± 5.34 | **<.001** | | | |
| Platelet count | 271.69 ± 85.69 | 247.55 ± 94.16 | **<.001** | | | |
| INR | 1.04 ± 0.18 | 1.07 ± 0.18 | **<.001** | | | |
| PTT | 28.64 ± 5.18 | 29.2 ± 7.03 | .187 | | | |
| Operative time | 112.34 ± 51.13 | 125.23 ± 58.63 | **<.001** | | | |
| Length of stay | 5.3 ± 5.3 | 1.9 ± 3.4 | **<.001** | | | |

*ASA*, American Society of Anesthesiologists; *COPD*, chronic obstructive pulmonary disease; *CHF*, congestive heart failure; *BMI*, body mass index; *BUN*, blood urea nitrogen; *WBC*, white blood cell; *INR*, international normalized ratio; *PTT*, partial thromboplastin time; *CI*, confidence interval.
Bold indicates *P* value <.05.

**Table VI**
Comparison of Serious Adverse Complications by CPT code.

| CPT | Serious adverse complication | | Total | *P* |
|---|---|---|---|---|
| | No (N, (%)) | Yes (N, (%)) | | |
| 23470 | 320 (95.0%) | 17 (5.0%) | 337 | <.001 |
| 23472 | 2071 (89.8%) | 234 (10.2%) | 2305 | |
| 23615 | 3694 (94.4%) | 218 (5.6%) | 3912 | |
| 23616 | 188 (89.5%) | 22 (10.5%) | 210 | |
| 23630 | 494 (97.8%) | 11 (2.2%) | 505 | |
| 23670 | 101 (94.4%) | 6 (5.6%) | 107 | |
| 23680 | 94 (96.9%) | 3 (3.1%) | 97 | |

*CPT*, current procedural terminology.

outcomes not only after proximal humerus fracture, but for orthopedic conditions as a whole.

Perhaps unsurprisingly, patient age at presentation constituted the third most important feature for predicting prolonged LOS and serious adverse complications within 30-days of surgery for proximal humerus fracture. There has been substantial research investigating the relationships between age, prolonged LOS, and serious adverse complications after proximal humerus fracture. Notably, Shields et al conducted a study using the American College of Surgeons-National Surgical Quality Improvement Program database from 2005 to 2010 and reported that age >60 years elevated the risk of major complication (OR 1.52; 95% CI 1.11-2.10, $P = .010$).[47] Similarly, Arvind et al determined age >65 years to be the second most important feature in their model predicting 30-day readmission after total shoulder arthroplasty. Other studies evaluating patient age have reported similar results with regard to its association with postoperative outcomes. For example, in a recent investigation by Malik et al, patients over the age of 65 were more likely to be discharged to a nonhome destination, with risk of nonhome discharge rising further as age increased (66-80 y.o.: OR 2.68, 95% CI 1.91-3.76, $P < .001$; 81-89 y.o.: OR 6.85, 95% CI 4.52-10.37, $P < .001$; ≥90 y.o.: OR 25.08, 95% CI 8.56-73.47, $P < .001$).[33] A plausible explanation for age's role in the model may be that a patient's baseline function, often closely linked to age, plays a crucial role in determining frailty. Previous literature consistently demonstrates that higher levels of frailty are strongly linked to greater risk of postoperative morbidity and mortality[27,51]; however, the role of chronological age has come under scrutiny with recent research suggesting similar outcomes after proximal humerus fracture fixation.[16]

Operative time was identified as another important factor in determining prolonged LOS and serious adverse complications after proximal humerus fracture treatment. Several studies have investigated the relationship between operative time and prolonged LOS or serious adverse complications after orthopedic procedures. Longer procedural times have repeatedly been associated with an increase in postsurgical complication rates and occasionally with prolonged LOS.[3,9,11,23] Most recently, Wilson et al determined that for each 20-minute increase in operative time during total shoulder arthroplasty, rates of any complication significantly increased (RR 1.24, 95% CI 1.19-1.26, $P < .001$).[50] Bohl et al echoed these findings, noting that a 15-minute increase in operative time increased the risk of postoperative complication, hospital readmission, and prolonged LOS after total joint arthroplasty.[2] The incorporation of multiple procedures (e.g., ORIF, TSA, etc.) in the current study may have influenced operative times, thereby affecting LOS and serious adverse event risk, potentially confounding these results. However, it is crucial to note that operative time exhibited greater predictive importance in these

**Table VII**
Demographics readmission.

| | No readmission (n = 7187) | Readmission (n = 286) | *P* value | 95% CI | | |
|---|---|---|---|---|---|---|
| | | | | Odds ratio | Lower limit | Upper limit |
| Sex (F) | 5384 (74.9%) | 199 (69.6%) | **.042** | 1.31 | 1.01 | 1.69 |
| Race (White) | 5649 (78.6%) | 226 (79.0%) | .685 | 1.03 | 0.77 | 1.37 |
| Diabetes (YES) | 1449 (20.2%) | 73 (25.5%) | **.027** | 1.36 | 1.03 | 1.78 |
| Smoker (YES) | 1286 (17.9%) | 62 (21.7%) | .103 | 1.27 | 0.95 | 1.69 |
| Functionally independent (YES) | 6811 (94.8%) | 246 (86.0%) | **<.001** | 0.34 | 0.24 | 0.48 |
| ASA class (>=3) | 321 (4.5%) | 4 (1.4%) | **<.001** | 2.99 | 2.26 | 3.95 |
| COPD (YES) | 411 (5.7%) | 36 (12.6%) | **<.001** | 2.37 | 1.65 | 3.41 |
| CHF (YES) | 91 (1.3%) | 5 (1.7%) | .478 | 0.39 | 0.56 | 3.44 |
| Hypertension on medication (YES) | 3782 (52.6%) | 177 (61.9%) | **.002** | 1.46 | 1.15 | 1.86 |
| Dialysis (YES) | 18 (0.3%) | 6 (2.1%) | **<.001** | 8.54 | 3.36 | 21.67 |
| Steroid (YES) | 253 (3.5%) | 11 (3.9%) | .770 | 1.10 | 0.59 | 2.03 |
| Bleeding disorder (YES) | 262 (3.7%) | 20 (7.0%) | **.004** | 1.99 | 1.24 | 3.18 |
| Transfusion (YES) | 66 (0.9%) | 16 (5.6%) | **<.001** | 6.39 | 3.65 | 11.19 |
| Preoperative sepsis (YES) | 225 (3.5%) | 11 (3.8%) | .74 | 1.11 | 0.6 | 2.05 |
| Age | 65.01 ± 13.65 | 69.31 ± 13.99 | **<.001** | | | |
| BMI | 29.69 ± 7.38 | 29.35 ± 7.68 | .430 | | | |
| Sodium | 137.98 ± 3.44 | 137.23 ± 4.18 | **.002** | | | |
| BUN | 17.32 ± 8.80 | 19.42 ± 12.22 | .055 | | | |
| Creatinine | 0.86 ± 0.40 | 1.04 ± 0.84 | **<.001** | | | |
| Albumin | 3.80 ± 0.52 | 3.38 ± 0.61 | **<.001** | | | |
| Bilirubin | 0.68 ± 0.59 | 0.85 ± 1.16 | .650 | | | |
| Serum Glutamic-Oxaloacetic Transaminase (SGOT) | 32.27 ± 40.21 | 37.77 ± 39.66 | .251 | | | |
| Alkaline phosphatase | 90.62 ± 43.98 | 107.53 ± 65.84 | **<.001** | | | |
| WBC | 8.83 ± 3.19 | 8.53 ± 3.35 | .068 | | | |
| Hematocrit | 36.88 ± 50.9 | 33.89 ± 5.77 | **<.001** | | | |
| Platelet count | 260.39 ± 89.36 | 250.64 ± 115.74 | **.005** | | | |
| INR | 1.06 ± 0.18 | 1.08 ± 1.89 | .068 | | | |
| PTT | 28.91 ± 6.39 | 30.11 ± 5.53 | **.016** | | | |
| Operative time | 117.80 ± 55.00 | 117.48 ± 49.11 | .491 | | | |
| Length of stay | 3.7 ± 4.1 | 2.1 ± 3.7 | **<.001** | | | |

*ASA*, American Society of Anesthesiologists; *COPD*, chronic obstructive pulmonary disease; *CHF*, congestive heart failure; *BMI*, body mass index; *BUN*, blood urea nitrogen; *WBC*, white blood cell; *INR*, international normalized ratio; *CI*, confidence interval.
Bold indicates *P* value <.05.

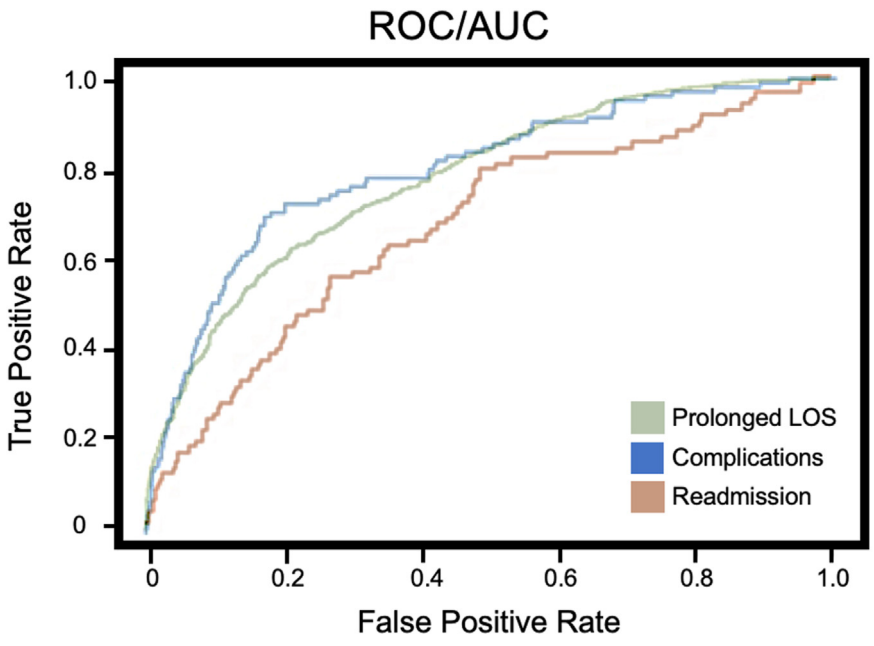


**Figure 1** Combined ROC/AUC graph for selected prediction models. *ROC*, receiver operating curve; *AUC*, area under the curve; *LOS*, length of stay.

models compared to CPT, indicating that a longer duration of surgery, regardless of the specific procedure performed, had a more significant impact on risk for prolonged LOS and the occurrence of serious adverse complications.

This study has several important limitations that should be taken into consideration. Firstly, the development of these algorithms relied solely on patients from the NSQIP database, and the generalizability of the findings is contingent upon robust external

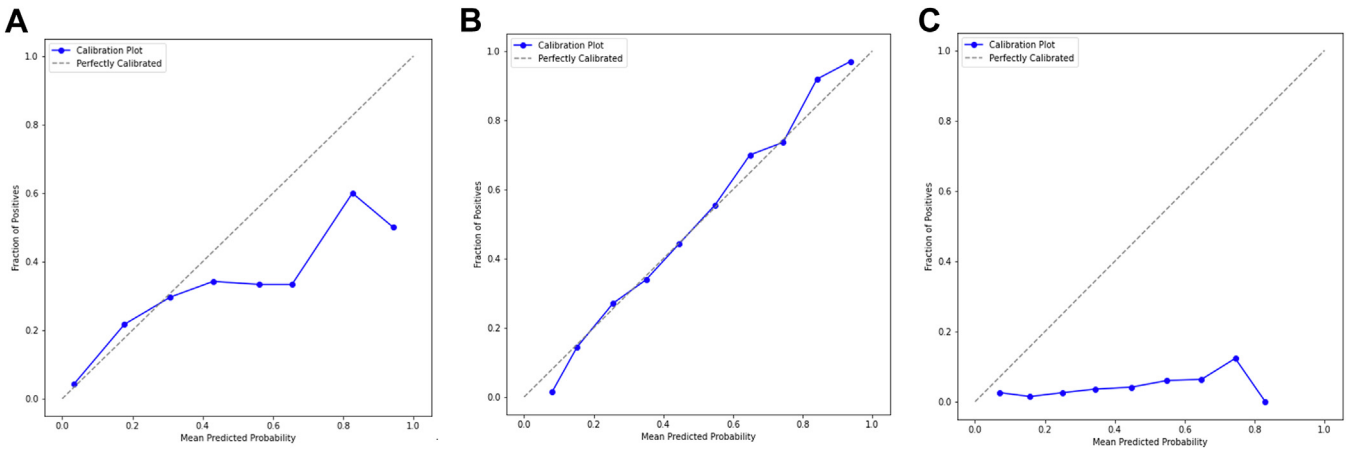


**Figure 2** Calibration plots for selected models (**A**) prolonged length of stay, (**B**) serious adverse complications, and (**C**) readmission.

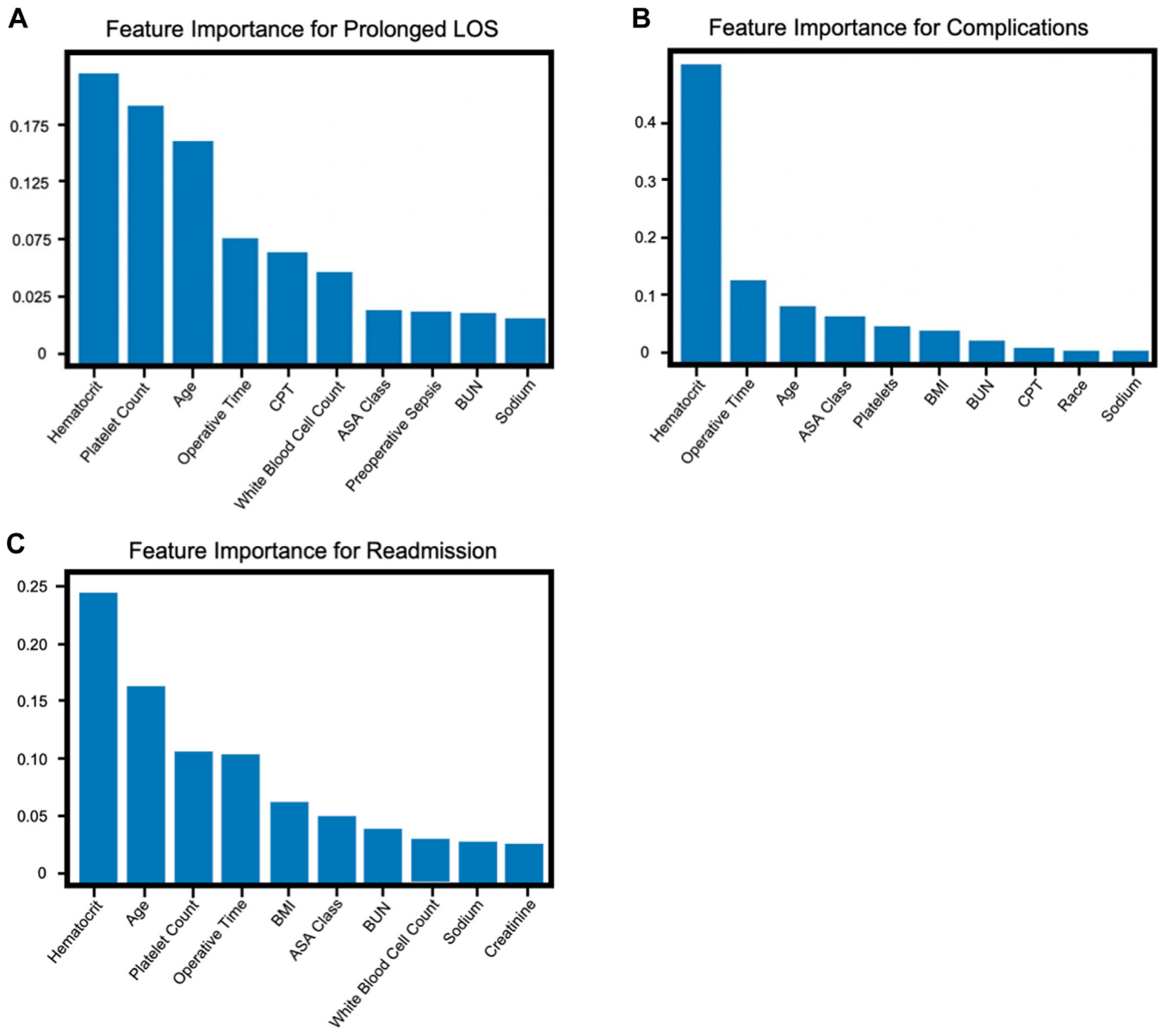


**Figure 3** Bar graphs illustrating feature importance for selected ML models predicting (**A**) prolonged length of stay, (**B**) serious adverse complications, and (**C**) readmission. *ML*, machine learning; *LOS*, length of stay; *CPT*, current procedural terminology; *ASA*, American Society of Anesthesiologists; *BUN*, blood urea nitrogen; *BMI*, body mass index.

validation studies using similar databases. Secondly, the lack of more detailed information within the NSQIP dataset precluded analysis of specific factors such as radiographic findings (e.g., fracture severity), surgical approach (e.g., deltopectoral or deltoid splitting), and implant, which may impact postoperative outcomes after proximal humerus fracture treatment. Incorporating these factors into these models could potentially enhance their accuracy and reliability. Thirdly, while certain modifiable risk factors such as hematocrit or platelet count were identified, it is important to note that many of the most important predictive factors are non-modifiable and cannot be manipulated with the goal of improving outcomes. Finally, when utilizing a comprehensive database like the NSQIP database, it is essential to acknowledge inherent potential limitations, including coding errors, missing data points, and inaccuracies within the provided information. The presence of sample bias indicates that the predictions of the ML model are only as reliable as the training dataset. To mitigate this, we employed validated imputation techniques in our analysis, as multiple studies in the literature have demonstrated the advantages of multiple imputation over complete case analysis. Complete case analysis can lead to inefficient utilization of data, potentially exacerbating existing health-care disparities and potentially yielding biased models. To strengthen the robustness of these findings, future investigations should prioritize external validation of predictive models using distinct populations. This would provide valuable insights into the performance and generalizability of the algorithm across diverse patient cohorts.

## Conclusion

Predictive models constructed using ML techniques demonstrated favorable discrimination and satisfactory-to-excellent performance in forecasting prolonged LOS and serious adverse complications occurring within 30 days of surgical intervention for proximal humerus fracture. Furthermore, modifiable preoperative factors such as hematocrit and platelet count were identified as significant predictive features, suggesting that clinicians could address these factors during preoperative patient optimization to enhance outcomes. Conversely, the model aiming to predict 30-day readmission encountered limitations due to small sample size, resulting in comparatively poor performance. Overall, these findings highlight the potential for ML techniques to enhance preoperative management, facilitate shared decision-making, and enable more effective and personalized orthopedic care by exploring alternative approaches to risk stratification.

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