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ORIGINAL ARTICLE

OPTIModel scoring for metastatic bone tumors: A data-driven tool for surgical planning and prognosis

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Metastatic bone tumors represent a significant clinical challenge, particularly when they affect the diaphysis of long bones. These lesions most commonly originate from primary malignancies such as breast, lung, prostate, renal, and thyroid cancers, which have a high propensity for bone dissemination due to their biological behavior and microenvironmental interactions.[1,2] The involvement of long bone diaphysis in metastatic disease often results in severe pain, structural instability, and an increased risk of pathological fractures, all of which contribute to a marked

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ABSTRACT

Objectives: This study aims to evaluate the predictive accuracy and clinical applicability of the OPTIModel Scoring System in Turkish patients with long bone diaphyseal metastases and to compare its survival predictions and surgical recommendations with real-world outcomes.

Patients and methods: Between April 2013 and June 2021, a total of 108 patients (52 males, 56 females; mean age: 64.5±10.6 years; range, 45 to 83 years) with histologically confirmed metastatic bone disease affecting the diaphysis of long bones and who underwent surgical treatment were retrospectively analyzed. The OPTIModel Scoring System was applied to estimate survival and guide surgical planning. The prognostic accuracy of the model was statistically analyzed. The patients were stratified into low-, intermediate-, and high-risk groups based on their predicted survival.

Results: The most common primary tumors were breast (24.1%), lung (23.1%), and multiple myeloma (13.0%). The femur (46.3%) was the most frequently affected site. The OPTIModel-predicted median survival was 10 months (95% confidence interval [CI]: 7.9-12.1), comparable to the real-world median survival of 13 months (95% CI: 10.8-15.2). Agreement between OPTIModel's surgical recommendations and real-world procedures was substantial (kappa [κ]=0.74, 95% CI: 0.63-0.85, p<0.001). The Kaplan-Meier analysis revealed no significant difference between predicted and real-world survival distributions (p=0.126). The ROC analysis yielded an area under the curve [AUC] of 0.61 (95% CI: 0.52-0.70), indicating moderate prognostic accuracy.

Conclusion: The OPTIModel Scoring System demonstrated substantial agreement with real-world surgical decisions and moderate accuracy in survival prediction for Turkish patients with metastatic long bone diaphyseal tumors. While the model provides valuable insights for clinical decision-making, further refinements incorporating emerging oncological advancements and biomarker-based risk stratification are needed. Future multi-ethnic validation studies are essential to enhance its applicability in diverse populations.

Keywords: Machine learning in medicine, metastatic bone tumors, OPTIModel Scoring System, orthopedic oncology, prognostic modeling, surgical decision-making, survival prediction.

decline in patients' functional status and overall quality of life.[3] Moreover, skeletal-related events (SREs), including pathological fractures, spinal cord compression, and hypercalcemia, are associated with higher morbidity and mortality, necessitating a multidisciplinary approach to optimize patient management.[4] While systemic treatments such as chemotherapy, targeted therapy, and bone-modifying agents (e.g., bisphosphonates, denosumab) are essential for controlling disease progression, surgical intervention remains a crucial component in patients with impending or completed fractures. The decision to proceed with surgery, however, requires a careful evaluation of patient prognosis to ensure that the benefits of an invasive procedure outweigh the risks, particularly in cases with limited life expectancy.[5-7]

Several scoring systems have been developed to estimate survival in patients with skeletal metastases, aiding clinicians in determining the most appropriate treatment approach. Prognostic models such as the Mirels' score, Tokuhashi score, and Bauer score have been widely used to assess the likelihood of fracture risk and survival duration, thereby guiding surgical decision-making.[5,8-11] However, these models are often criticized for their limited applicability across diverse patient populations and their inability to incorporate advancements in oncological therapies which have significantly altered survival outcomes over the years.[11] Additionally, many of these traditional models rely on subjective parameters, potentially leading to interobserver variability in clinical assessments.[12] Recognizing these limitations, the OPTIModel scoring system has been introduced as a novel prognostic tool that integrates a broader range of clinical, oncological, and biochemical parameters to enhance mortality prediction and facilitate personalized treatment planning.[13-19] Unlike its predecessors, OPTIModel employs a data-driven approach by incorporating machine-learning algorithms and large-scale patient databases, potentially improving its predictive accuracy across different demographic groups.[20-23]

Despite its potential advantages, the applicability of the OPTIModel scoring system in specific populations, such as the Turkish cohort, remains uncertain. Population-specific variations, including genetic predispositions, cancer epidemiology, and healthcare infrastructure, can significantly influence the accuracy and generalizability of predictive models.[24] To illustrate, differences in the prevalence of primary cancers leading to skeletal metastases, access to advanced oncological treatments, and patient adherence to therapeutic interventions may impact survival outcomes in Turkish patients compared to Western cohorts.[25-27] Furthermore, cultural and socioeconomic factors play a role in treatment decision-making, which could affect the performance of predictive algorithms developed in different healthcare settings.[28,29] Given these considerations, it is crucial to validate and assess the real-world utility of OPTIModel in Turkish patients with metastatic bone tumors involving long bone diaphysis.

Unlike traditional scoring systems such as Mirels, Tokuhashi, or Bauer, which primarily focus on subjective clinical indicators and imaging findings, OPTIModel incorporates objective biochemical markers, tumor characteristics (primary cancer type, visceral involvement), and uses machine-learning algorithms for survival prediction and surgical recommendation. More contemporary models like SORG and PATHFx also integrate laboratory values and demographic factors, but OPTIModel differs in its emphasis on real-time artificial intelligence (AI)-assisted decision-making and its ability to stratify patients into risk-adapted surgical categories. While PATHFx utilizes Bayesian networks and SPRING focuses on spinal metastases, OPTIModel is designed specifically for appendicular skeletal metastases involving the long bones (Table I).

Additionally, the generalizability of predictive models like OPTIModel may be affected by population-specific factors. The Turkish healthcare system is characterized by a mixed public-private structure with centralized cancer registries and state-sponsored oncological treatments. However, regional disparities in healthcare access, delayed referrals, and variable uptake of advanced therapies may impact real-world survival outcomes. Moreover, differences in cancer epidemiology (e.g., higher prevalence of breast and lung cancer in females), sociocultural beliefs influencing surgical consent, and resource availability (e.g., endoprosthetic implants) must be considered when applying AI-based models developed in Western populations to Turkish patients.

In the present study, we aimed to evaluate the OPTIModel scoring system's prognostic accuracy in Turkish patients by comparing it with real-world clinical outcomes and to determine its reliability in mortality prediction and surgical planning, in

TABLE I
Baseline clinical and demographic characteristics of patients with metastatic bone tumors

Model	Type of inputs	Machine learning	Application area	Limitation
Mirels	Subjective clinical + radiographic	No	Impending fracture risk	No survival estimation
Tokuhashi	Neurological + visceral + performance	No	Spinal metastases	Lacks biomarker integration
SORG	Demographics + tumor + labs	Yes	Skeletal metastases (general)	May overfit in some subgroups
PATHFx	Demographics + labs + metastasis	Yes (Bayesian)	Various metastatic settings	Requires online tool access
SPRING	Spine-focused parameters	Yes	Vertebral metastases	Not for long bones
OPTIModel	Clinical + oncological + biochemical markers	Yes (ML-integrated)	Long bone diaphyseal metastases	Requires validation in diverse populations

order to assess its potential for integration into routine practice for improved patient management.

PATIENTS AND METHODS

This multi-center, retrospective study was conducted in five out of eight centers: Necmettin Erbakan University Faculty of Medicine, Adnan Menderes University Faculty of Medicine, Ege University Faculty of Medicine, Kocaeli University Faculty of Medicine, and Selçuk University Faculty of Medicine, Department of Orthopedics and Traumatology, between April 2013 and June 2021. The study included patients who underwent surgical treatment for metastatic bone tumors in the diaphysis of long bones. The medical records of a total of 108 patients (52 males, 56 females; mean age: 64.5±10.6 years; range, 45 to 83 years) with histologically confirmed metastatic bone disease affecting the diaphysis of long bones were reviewed. Patients aged 18 years or older with a primary malignancy which was metastasized to the diaphysis of long bones and who underwent surgical intervention, including internal fixation, endoprosthetic replacement, or tumor resection for pathological or impending fractures, were included in the study. Only patients with complete clinical data, follow-up information, and mortality records were considered eligible. Patients with primary bone tumors or hematological malignancies were excluded. Additionally, those with incomplete medical records or who were lost to follow-up, as well as patients treated non-surgically through palliative radiotherapy or medical management alone, were excluded. Patients with missing key clinical variables, survival data, or incomplete surgical documentation were also excluded using listwise deletion. No imputation methods were employed due to the completeness threshold of the dataset. The study flowchart is shown in Figure 1. Written informed consent was obtained from each patient. The study protocol was approved by the Necmettin Erbakan University Non-Drug and Medical Device Research Ethics Committee (Date: 07.02.2025, No: 2025/5531). The study was conducted in accordance with the principles of the Declaration of Helsinki.

For each patient, demographic, clinical, and surgical data were collected. The affected bone, the type of surgical treatment performed, and real-world postoperative survival in months were documented. Furthermore, the OPTIModel scoring system was applied to determine the recommended treatment

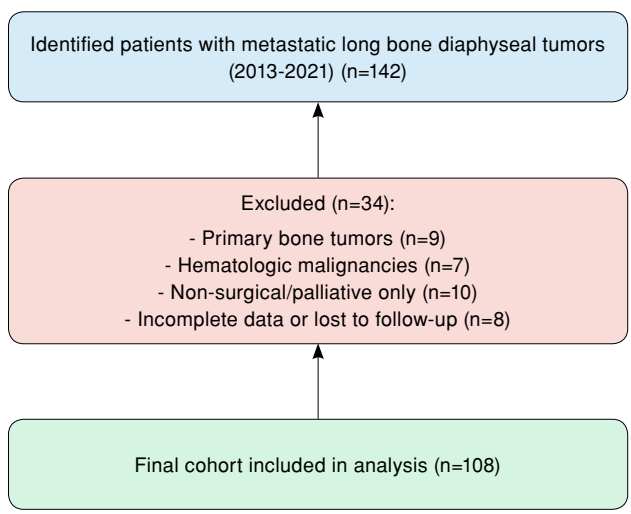


FIGURE 1. Flowchart of study population selection.

approach and estimate patient survival, and these predictions were compared with real-world clinical outcomes.

Application of the OPTIModel scoring system

The OPTIModel application, developed by Leiden University Medical Center (LUMC), is designed to assist clinicians in treatment planning for patients with long bone metastases. The application provides a flowchart to estimate the patient's expected survival and subsequently offers localized treatment recommendations based on the location, dissemination, and presentation of the metastases.[30] The OPTIModel scoring system was accessed through the mobile application developed by Leiden University Medical Center (App Store version 1.3.2, last updated 2024). The scoring was applied retrospectively based on patient records at the time of diagnosis. No prospective cases were included in the analysis.

The OPTIModel scoring system was applied to all 108 patients at the time of diagnosis to estimate survival and guide treatment decisions. The system integrates clinical, oncological, and biochemical parameters to predict patient survival and recommend appropriate surgical strategies. The predicted survival times and treatment recommendations generated by the OPTIModel system were compared with real-world patient outcomes recorded in follow- up.[20] To assess inter-rater reliability, two independent orthopedic oncologists scored a random 20% subsample of the cohort using the OPTIModel tool. The inter-rater agreement was substantial (kappa [κ]=0.79, 95% confidence interval [CI]: 0.65–0.91), supporting the consistency of model application.

The patients were stratified into low-risk, intermediate-risk, and high-risk groups based on their OPTIModel-predicted survival. Surgical decisions were categorized as follows:

1. Curative or long-term reconstructive surgery (e.g., endoprosthetic reconstruction) for patients with an expected survival >12 months,
2. Palliative internal fixation (e.g., intramedullary nailing, plate fixation) for patients with intermediate survival (3 to 12 months),
3. Minimally invasive or supportive treatment for patients with a poor prognosis (<3 months).

Statistical analysis

Statistical analysis was performed using the IBM SPSS version 27.0 software (IBM Corp., Armonk, NY, USA) and R software (R Foundation for Statistical Computing, Vienna, Austria). Continuous variables were expressed in mean ± standard deviation (SD) or median (min-max), while categorical variables were expressed in number and frequency. The primary outcome of the study was real-world postoperative survival, which was compared with the OPTIModel-predicted survival estimates using the Kaplan-Meier survival analysis. The log-rank test was applied to determine statistical differences between the predicted and real-world survival distributions. To assess the agreement between OPTIModel's surgical recommendations and real-world clinical decisions, Cohen's κ coefficient was calculated, with values above 0.61 indicating substantial agreement. Post-hoc power analysis using the κ value (0.74) with alpha=0.05 and n=108 yielded a power of 0.91, indicating sufficient statistical power to detect substantial agreement. The prognostic accuracy of OPTIModel in predicting mortality was evaluated using the receiver operating characteristic (ROC) curve analysis, with the area under the curve (AUC) used as a measure of predictive performance. The Cohen's κ coefficient was reported with 95% CI, and AUC values were similarly presented to ensure statistical precision. Additionally, the patients were stratified into low-risk (>12 months survival), intermediate-risk (3 to 12 months), and high-risk (<3 months) groups, and a chi-square test was performed to assess the statistical significance of differences between OPTIModel's survival classifications and real-world patient outcomes. A p value of <0.05 was considered statistically significant.

RESULTS

Sociodemographic characteristics and clinical data of patients with metastatic bone tumors are shown in Table II. The most common primary malignancies leading to bone metastases were breast cancer (24.1%), lung cancer (23.1%), and multiple myeloma (13.0%). Other primary cancers included renal cell carcinoma (9.3%), liver tumors (7.4%), and thyroid cancer (4.6%). Regarding affected bones, the femur was the most commonly involved site (46.3%), followed by the humerus (18.5%), and cases with combined humerus and femur diaphyseal involvement (25.9%). In terms

TABLE II
Comparison between OPTIModel recommendations and real-world surgical interventions (n=108)

Parameters	n	%	Mean±SD	Median	Min-Max
Age (year)			64.5±10.6		45-83
Sex					
Male	52	48.1			
Female	56	51.9			
Diagnosis					
Breast cancer	26	24.1			
Lung cancer	25	23.1			
Multiple myeloma	14	13.0			
Renal cell carcinoma	10	9.3			
Liver tumor	8	7.4			
Thyroid cancer	5	4.6			
Bladder tumor	4	3.7			
Prostate tumor	4	3.7			
Others	12	11.1			
Affected bone					
Femur	50	46.3			
Humerus	20	18.5			
Humerus and femur diaphysis	28	25.9			
Others	10	9.3			
Real-world surgery					
Nail	43	39.8			
Prosthesis	20	18.5			
Plate	19	17.6			
Plate + cement	16	14.8			
Nail + cement	9	8.3			
Prosthesis + cement	1	0.9			
Patient survival (month)				13	1-132
OPTIModel recommendation					
Nail	40	37.0			
Prosthesis	18	16.7			
Plate	20	18.5			
Plate + cement	15	13.9			
Nail + cement	10	9.3			
Prosthesis + cement	5	4.6			
OPTIModel-predicted survival (month)				10	1-118

SD: Standard deviation.

of surgical interventions, the most frequently performed procedures were nail fixation (39.8%), prosthetic replacement (18.5%), and plate fixation (17.6%). The median real-world survival following surgery was 13 (range, 1 to 132) months. The OPTIModel Scoring System predicted a median survival of 10 (range, 1 to 118) months. The model recommended nail fixation for 37.0% of patients, prosthetic replacement for 16.7%, and plate fixation for 18.5% (Table II).

Comparison of OPTIModel Scoring System with real-world surgical outcomes is shown in Table III. The most frequently recommended and performed procedure was nail fixation, accounting for 37.0% of the OPTIModel recommendations and 39.8% of real-world surgeries. Similarly, prosthetic replacement and plate fixation were suggested in 16.7% and 18.5% of cases, respectively, aligning closely with the real-world surgical rates of 18.5% and 17.6%. The Cohen's κ coefficient (κ=0.74) indicated substantial agreement between

TABLE III
Comparison of OPTIModel scoring system with real-world surgical outcomes (n=108)

	OPTIModel scoring system		Real-world surgery		
	n	%	n	%	*p*
Surgical procedures					0.911
Nail	40	37.0	43	39.8	
Prosthesis	18	16.7	20	18.5	
Plate	20	18.5	19	17.6	
Plate + cement	15	13.9	16	14.8	
Nail + cement	10	9.3	9	8.3	
Prosthesis + cement	5	4.6	1	0.9	
Survival risk groups					0.854
Low-risk group (>12 month)	30	27.8	28	25.9	
Intermediate-risk group (4-12 month)	40	37.0	42	38.9	
High-risk group (<3 month)	38	35.2	38	35.2	

OPTIModel's predictions and real-world clinical decisions. Regarding survival risk stratification, the low-risk group (>12 months survival) comprised 27.8% of patients based on OPTIModel predictions compared to 25.9% in real-world data. Similarly, the intermediate-risk group (4 to 12 months) included 37.0% of cases in both the model and real-world survival data, whereas the high-risk group (<3 months survival) accounted for 35.2% in both categories (p=0.854). Notably, four patients classified as high-risk (predicted survival <3 months) survived beyond 12 months, highlighting potential model underestimation in select cases. These misclassifications underscore the importance of integrating clinical judgment alongside algorithmic predictions (Table III).

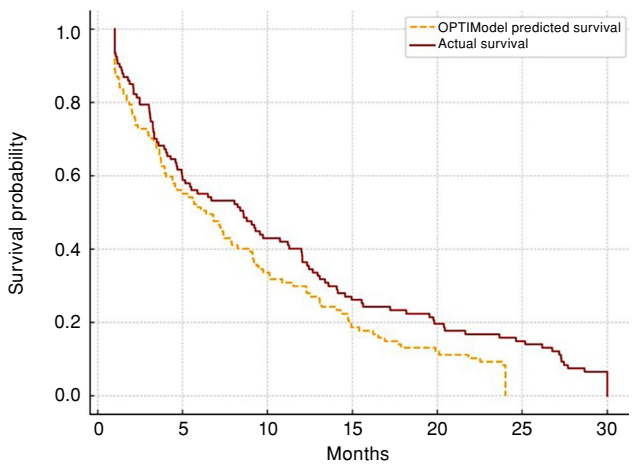


FIGURE 2. Kaplan-Meier survival analysis: OPTIModel Predictions versus real-world survival.

The Kaplan-Meier survival analysis, OPTIModel predictions versus real-world survival, is shown in Figure 2. The Kaplan-Meier survival analysis compares OPTIModel-predicted survival with real-world patient survival in the cohort. The dashed yellow line represents OPTIModel's estimated survival probabilities, while the solid brown line illustrates real-world survival outcomes. Initially, both curves exhibit a rapid decline, reflecting the high early mortality risk associated with long bone diaphyseal metastases. However, OPTIModel underestimates survival in some cases, particularly beyond the 10-month mark, as indicated by the divergence of the curves. The real-world survival curve extends further, suggesting that some patients outlived the model's predictions. The log-rank test (p>0.05) indicates that there was no statistically significant difference between OPTIModel-predicted and real-world survival distributions, suggesting that the model provides a reasonable estimation of patient prognosis. Despite minor deviations, the overall trend of both curves remains similar, reinforcing the clinical utility of the OPTIModel Scoring System in mortality prediction (Figure 2).

Subgroup survival analysis revealed that patients with breast cancer had the highest median postoperative survival (17 months), followed by multiple myeloma (14 months) and lung cancer (9 months). Among surgical interventions, patients receiving endoprosthetic reconstruction showed a longer median survival (16 months) compared to nail fixation (11 months) and plate fixation (10 months). Risk stratification based on OPTIModel scoring aligned well with survival

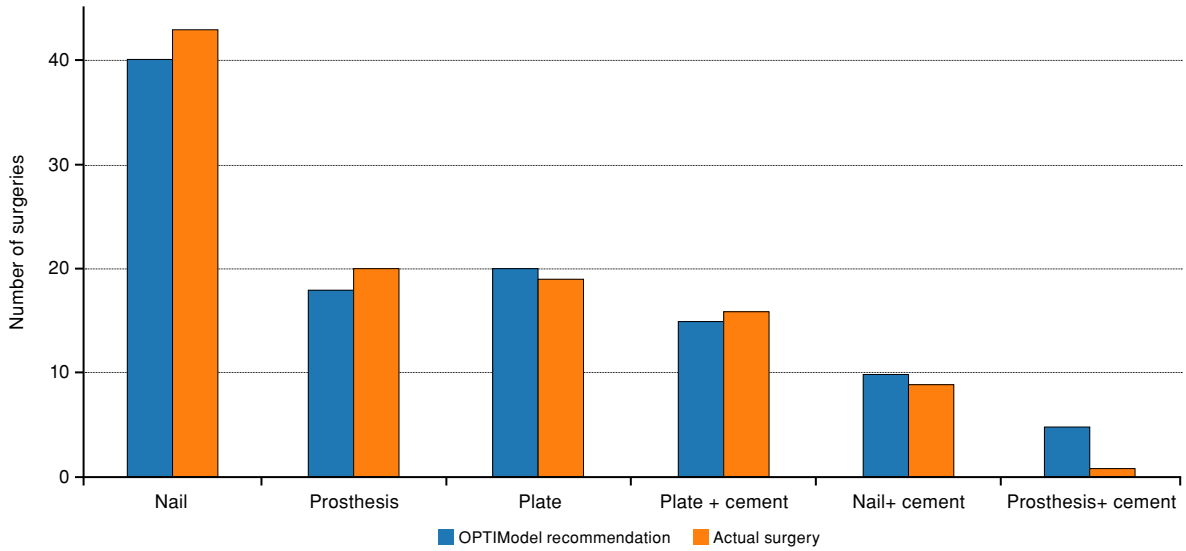


FIGURE 3. Comparison of OPTIModel predictions versus real-world surgeries (Cohen's Kappa = 0.74).

trends: low-risk patients had a median survival of 21 months, intermediate-risk 10 months, and high-risk three months.

Comparison of OPTIModel predictions versus real-world surgeries is shown in Figure 2. The most frequently recommended and performed procedure was nail fixation, comprising 37.0% of OPTIModel predictions and 39.8% of real-world surgeries, demonstrating a strong correlation between model recommendations and real-world practice. Similarly, prosthetic replacement (16.7% *vs.* 18.5%) and plate fixation (18.5% *vs.* 17.6%) exhibited minimal deviation between model predictions and real-world decisions. However, OPTIModel overestimated the use of prosthesis + cement (4.6%) compared to its real-world application (0.9%), suggesting a potential limitation in its predictive accuracy for certain surgical approaches. The Cohen's κ coefficient (κ=0.74) indicates substantial agreement between OPTIModel-predicted and real-world surgical decisions. The Cohen's κ was calculated as 0.74 (95% CI: 0.63-0.85), indicating substantial agreement. Among 108 patients, the treatment recommendations of the model matched real-world surgical decisions in 89 cases (concordant), while 19 cases were discordant (Figure 3).

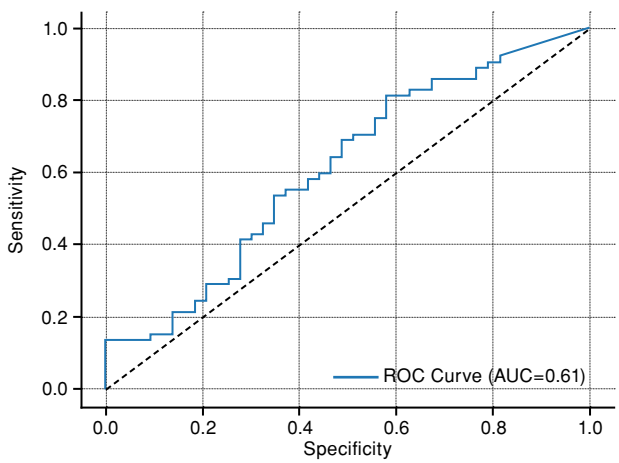


FIGURE 4. OPTIModel's accuracy in mortality prediction, a receiver operating characteristic (ROC) curve analysis.

Prognostic accuracy of the model

The OPTIModel's accuracy in mortality prediction, a ROC curve analysis is shown in Figure 4. Although the ROC analysis yielded an AUC of 0.61 (95% CI: 0.52-0.70), indicating moderate prognostic discrimination, this value was near the lower threshold of acceptability and suggests limited precision in individual-level survival prediction (Figure 4).

DISCUSSION

In the present study, we evaluated the clinical utility and prognostic accuracy of the OPTIModel Scoring System in Turkish patients with long bone diaphyseal metastatic tumors. By comparing OPTIModel's survival predictions and surgical recommendations with real-world clinical outcomes, our findings provide insights into its potential integration into routine surgical decision-making.

Several prognostic scoring systems have been proposed to guide treatment decisions in patients with metastatic bone disease, including the Mirels' score, Tokuhashi score, and Bauer score. These models primarily focus on fracture risk assessment and survival estimation, yet they have been criticized for their limited adaptability to modern oncological advancements and their reliance on subjective clinical parameters.[22,31] In contrast, OPTIModel integrates a data-driven approach, incorporating a broader range of clinical and biochemical markers, potentially improving predictive accuracy.[21] Our study found a substantial agreement (κ=0.74) between OPTIModel's surgical recommendations and real-world surgical interventions, similar to previous findings by Ben Gal et al.[22] who reported that machine-learning-based prediction models demonstrated greater consistency with clinical decisions than traditional scoring systems. Furthermore, Park et al.[21] compared several survival prediction models and found that those incorporating biochemical and systemic inflammatory markers, such as OPTIModel, had higher discriminative ability than conventional models. These findings highlighted the growing role of AI-assisted prognosis tools in modern orthopedic oncology. This underestimation may be partly explained by recent advances in systemic therapy, including immunotherapy and targeted agents, which have significantly prolonged survival in patients with metastatic bone disease. Additionally, the Turkish treatment landscape, characterized by national access to updated oncology protocols and earlier surgical interventions in certain regions, may have contributed to extended survival not captured by the original training data of the model.

In our study, the Kaplan-Meier survival analysis revealed that while OPTIModel-predicted survival trends closely aligned with real-world survival, it underestimated survival in some cases beyond 10 months. This divergence suggests that certain patients outlived model predictions, which is consistent with findings by Meares et al.,[23] who reported that static scoring systems tend to underestimate survival in patients responding well to systemic therapies. Alfaro et al.[20] observed similar limitations in models when applied to diverse patient populations. These discrepancies may be explained by recent advancements in systemic therapies, improved bone-targeting agents, and better supportive care, factors that are not always incorporated into predictive models.[10,11] Future iterations of OPTIModel may require continuous recalibration to accommodate real-world clinical changes, as suggested by Weschenfelder et al.[15]

A critical application of prognostic scoring systems in metastatic bone disease is their role in surgical planning. Current guidelines suggest that patients with a life expectancy exceeding 12 months should undergo curative or reconstructive surgery (e.g., endoprosthetic replacement), whereas those with shorter life expectancies may benefit more from palliative internal fixation.[32,33] Our study found that OPTIModel accurately stratified patients into low-risk, intermediate-risk, and high-risk groups, with no significant difference between predicted and real-world survival classifications. Similar findings were reported by Park et al.[21] demonstrated that AI-based prediction models accurately categorized patients into risk groups, thereby assisting clinicians in surgical decision-making. However, OPTIModel slightly overestimated the need for prosthesis + cement procedures, a discrepancy also observed by Christ et al.[10] The model's overestimation of prosthesis + cement procedures may reflect an algorithmic bias toward long-term reconstructive strategies. However, real-world deviations could also be influenced by institutional preferences, surgeon experience, and local resource availability. In some centers, less invasive options may be favored due to cost, patient fragility, or logistical constraints. This may indicate a bias in the algorithm toward more invasive interventions, emphasizing the need for further refinement in its surgical recommendations. Pagnotti et al.[11] suggested that optimizing machine-learning models with real-time clinical data updates could improve their predictive accuracy in such cases.

To date, several prognostic models, such as SORG, PATHFx, and SPRING, have been developed to guide survival prediction and surgical planning in patients with metastatic bone tumors.[20-23] The SORG score utilizes demographic data, tumor type, functional status, and laboratory markers to estimate average survival and has been validated in multiple studies as a reliable tool.[14] The PATHFx, a machine-learning-based model, provides dynamic survival predictions tailored to individual patient data.[22] However, literature suggests that this model may overestimate survival in some patient groups, particularly in oligometastatic disease cases.[23] The SPRING model is specifically designed for vertebral metastases

TABLE IV
Comparison of prognostic models in bone metastasis

Model	Inputs	ML-based	Site-specific	Limitations
SORG	Demographics, labs	Yes	General skeleton	Overfitting, may require updates
PATHFx	Bayesian + clinical/lab data	Yes	General skeleton	Relies on online infrastructure
SPRING	Spine-specific variables	Yes	Vertebral metastases	Not applicable to long bones
OPTIModel	Biochemical + oncological data	Yes	Long bone diaphyses	Underestimates survival in some patients

and is used to optimize surgical decision-making in these patients.[21] In comparison, OPTIModel differs from both traditional and modern scoring systems by incorporating biochemical markers, systemic inflammatory indices, and machine-learning algorithms. In the present study, the OPTIModel demonstrated substantial agreement with surgical decisions (κ=0.74) and provided reasonable survival estimates, although it tended to underestimate survival in certain patients. While models such as PATHFx, which integrate dynamic learning algorithms, may better adapt to evolving oncological treatments, OPTIModel may offer superior accuracy in specific patient cohorts. Therefore, future refinements of OPTIModel, potentially integrating aspects of SPRING and PATHFx models, or expanding its scope to include additional biochemical markers, could further enhance its predictive power. Furthermore, although subgroup survival outcomes (e.g., by tumor type and surgical approach) were analyzed, ROC analyses for these subgroups were not conducted due to limited sample sizes, which would have resulted in insufficient statistical power. However, our findings indicated that the OPTIModel system underestimated survival in patients with breast cancer and multiple myeloma, likely due to the benefits of recent systemic therapies not accounted for by the original model. Likewise, patients who underwent endoprosthetic reconstruction showed longer survival than predicted, suggesting a discrepancy between algorithmic recommendations and real-world outcomes in certain surgical contexts. These subgroup-specific differences underscored the necessity for dynamic recalibration of the model using updated clinical data. To reduce redundancy and improve clarity, a concise comparison of relevant prognostic models is summarized in Table IV, highlighting the specific focus and limitations of each model.

Our findings suggest that OPTIModel is a valuable tool for prognostic evaluation and surgical planning in patients with metastatic long bone diaphyseal tumors. However, its predictive accuracy can be further refined by incorporating emerging clinical parameters. The integration of systemic therapy advancements, including targeted therapy and immunotherapy, can improve survival predictions. Similarly, incorporating biomarkers reflecting tumor burden and systemic inflammatory response may enhance prognostic stratification. Additionally, considering patient-reported functional outcomes and quality of life measures in decision-making could further personalize surgical planning. Daher et al.[24] reported that factors such as cultural background, genetic predisposition, and healthcare system disparities played a significant role in cancer prognosis and treatment strategies. Therefore, OPTIModel should be validated in larger, multiethnic cohorts to determine its applicability beyond the current study population. Furthermore, Raza et al.[29] proposed that the development of a real-time adaptive AI model capable of continuously updating its predictions based on live clinical data could significantly enhance OPTIModel's utility in diverse healthcare settings.

Nonetheless, this study has some limitations. First, its retrospective design introduces inherent selection biases. Second, while OPTIModel predictions were compared with real-world clinical outcomes, real-world decision-making also considers patient preferences, surgeon experience, and institutional resources, factors that cannot be fully accounted for in a predictive algorithm. Additionally, we were unable to perform a multivariate analysis to identify independent predictors of surgical decision-making (e.g., patient age, tumor type, model recommendation) due to the sample size limitations. This analytical gap limited the ability to determine the relative influence

of clinical and algorithmic factors on real-world surgical choices. Future multi-center, large-scale, prospective studies may address this shortcoming to better understand the determinants of operative decision-making. Finally, our cohort was limited to the Turkish population, and while this provides valuable regional insights, external validation in other geographic and ethnic groups is necessary before widespread adoption.

In conclusion, our study contributes to the literature by validating the OPTIModel Scoring System in a non-Western population, assessing its alignment with real-world surgical decisions, and identifying its predictive limitations in extended survival cases. These findings underscore the importance of incorporating dynamic clinical variables into AI-based prognostic models and lay the foundation for future advancements in adaptive survival prediction tools for metastatic bone disease.

Data Sharing Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

1. Chen LP, Peng YX. Hidden blood loss of percutaneous vertebroplasty in the treatment of spinal metastases of breast cancer. Jt Dis Relat Surg 2025;36:535-42. doi: 10.52312/jdrs.2025.2393.
2. Macedo F, Ladeira K, Pinho F, Saraiva N, Bonito N, Pinto L, et al. Bone metastases: An overview. Oncol Rev 2017;11:321. doi: 10.4081/oncol.2017.321.
3. Johnson JD, Satcher RL, Feng L, Lewis VO, Moon BS, Bird JE, et al. What is the prosthetic survival after resection and intercalary endoprosthetic reconstruction for diaphyseal bone metastases of the humerus and femur? Clin Orthop Relat Res 2023;481:2200-10. doi: 10.1097/CORR.0000000000002669.
4. Kanellias N, Ntanasis-Stathopoulos I, Gavriatopoulou M, Koutoulidis V, Fotiou D, Migkou M, et al. Newly diagnosed multiple myeloma patients with skeletal-related events and abnormal MRI pattern have poor survival outcomes: A prospective study on 370 patients. J Clin Med 2022;11:3088. doi: 10.3390/jcm11113088.
5. Cappellari A, Trovarelli G, Crimì A, Pala E, Angelini A, Berizzi A, et al. New concepts in the surgical treatment of actual and impending pathological fractures in metastatic disease. Injury 2023;54 Suppl 1:S31-5. doi: 10.1016/j.injury.2020.11.025.
6. Kanazawa H. End-stage cancer patients diagnosed with a femoral pathological fracture on admission to palliative care units. Palliat Med Rep 2021;2:348-54. doi: 10.1089/pmr.2021.0052.
7. Hershkovich O, Sakhnini M, Barkay G, Liberman B, Friedlander A, Lotan R. Proximal femoral multiple myeloma pathological fractures, impending and actual fractures - a patient survival study. BMC Cancer 2024;24:917. doi: 10.1186/s12885-024-12681-0.
8. Mansour AA, El Mowafi MA, Azmy SI. A systematic review and meta-analysis of the predictive accuracy of preoperative scoring systems for postoperative survival in patients with metastatic bone disease. EOJ 2024;59:103-17.
9. Nguyễn MV, Carlier C, Nich C, Gouin F, Crenn V. Fracture risk of long bone metastases: A review of current and new decision-making tools for prophylactic surgery. Cancers (Basel) 2021;13:3662. doi: 10.3390/cancers13153662.
10. Christ AB, Piple AS, Gettleman BS, Duong A, Chen M, Wang JC, et al. Prevalence of primary malignant tumours, rates of pathological fracture, and mortality in the setting of metastatic bone disease. Bone Jt Open 2023;4:424-31. doi: 10.1302/2633-1462.46.BJO-2023-0042.R1.
11. Pagnotti GM, Trivedi T, Mohammad KS. Translational strategies to target metastatic bone disease. Cells 2022;11:1309. doi: 10.3390/cells11081309.
12. Lee KH, Lee RW, Yun JS, Kim MS, Choi HS. Automated diagnosis of knee osteoarthritis using ResNet101 on a DEEP:PHI: Leveraging a no-code AI platform for efficient and accurate medical image analysis. Diagnostics (Basel) 2024;14:2451. doi: 10.3390/diagnostics14212451.
13. Errani C. Treatment of bone metastasis. Curr Oncol 2022;29:5195-7. doi: 10.3390/curroncol29080411.
14. Fernández JC, Fernández PG-H, Negreira JM, González PA. Are the SORG and OPTImodel, Tokuhashi and Tomita algorithms still suitable as predictors of survival in patients with vertebral metastases in routine clinical practice? Preprints and Early-Stage Research 2025. doi: 10.22541/au.173883524.47342656/v1.
15. Weschenfelder W, Weschenfelder F, Spiegel C, Schrenk KG, Ernst T, Hofmann GO. Prognostic impact of oligometastases in orthopaedic surgery for metastatic bone disease. J Orthop Surg (Hong Kong) 2025;33:10225536251315983. doi: 10.1177/10225536251315983.
16. Mehnert E, Möller FS, Hofbauer C, Weidlich A, Winkler D, Troost EGC, et al. Palliative care of proximal femur metastatic disease and osteolytic lesions: Results following surgical and radiation treatment. BMC Cancer 2024;24:1431. doi: 10.1186/s12885-024-13170-0.
17. Atilgan N, Ipek B, Duman N, Orhan O, Yilmaz M. Can anterolateral thigh flap be a rescuer in lower extremity injuries? Eur Rev Med Pharmacol Sci 2023;27:7005-11. doi: 10.26355/eurrev_202308_33272.
18. Errani C, Cosentino M, Ciani G, Ferra L, Alfaro PA, Bordini B, et al. C-reactive protein and tumour diagnosis predict survival in patients treated surgically for long bone metastases. Int Orthop 2021;45:1337-46. doi: 10.1007/s00264-020-04921-2.

19. Simpson J, Kumar A. Metastases of the appendicular skeleton: an orthopaedic update. J Orthop Trauma 2021;35:152-62. doi: 10.1016/j.mporth.2021.03.004.
20. Alfaro PA, Delgado J, Dumas A, Mesa C, Wevar O, Herrera C, et al. Comparison between different prognostic models to be used for metastatic bone disease on appendicular skeleton in a Chilean population. Eur J Orthop Surg Traumatol 2021;31:1657-62. doi: 10.1007/s00590-021-03153-3.
21. Park JH, Won J, Kim HS, Kim Y, Kim S, Han I. Comparison of survival prediction models for bone metastases of the extremities following surgery. Bone Joint J 2024;106-B:203-11. doi: 10.1302/0301-620X.106B2.BJJ-2023-0751.
22. Ben Gal O, Soh TCF, Vaughan S, Jayasanker V, Mahendra A, Gupta S. The prediction of survival after surgical management of bone metastases of the extremities-a comparison of prognostic models. Curr Oncol 2022;29:4703-16. doi: 10.3390/curroncol29070373.
23. Meares C, Badran A, Dewar D. Prediction of survival after surgical management of femoral metastatic bone disease - A comparison of prognostic models. J Bone Oncol 2019;15:100225. doi: 10.1016/j.jbo.2019.100225.
24. Daher M, Zalaquett Z, Mekhael E, Aoun M, Chalhoub R, Abdo M, et al. Epidemiology of bone tumors in Lebanon: A retrospective study from 2000 to 2022 at a tertiary center. Future Sci OA 2023;9:FSO886. doi: 10.2144/fsoa-2023-0102.
25. Dogan I, Aksoy S, Cakar B, Basaran G, Ercelep O, Molinas Mandel N, et al. Demographic and clinical features of patients with metastatic breast cancer: A retrospective multicenter registry study of the Turkish Oncology Group. Cancers (Basel) 2023;15:1667. doi: 10.3390/cancers15061667.
26. Soran A, Dogan L, Isik A, Ozbas S, Trabulus DC, Demirci U, et al. The effect of primary surgery in patients with De Novo Stage IV breast cancer with bone metastasis only (Protocol BOMET MF 14-01): A multi-center, prospective registry study. Ann Surg Oncol 2021;28:5048-57. doi: 10.1245/s10434-021-09621-8.
27. Bolek H, Kuzu OF, Sertesen Camoz E, Sim S, Sekmek S, Karakas H, et al. Evaluating the prognostic role of glucose-to-lymphocyte ratio in patients with metastatic renal cell carcinoma treated with tyrosine kinase inhibitors in first line: A study by the Turkish Oncology Group Kidney Cancer Consortium (TKCC). Clin Transl Oncol 2025;27:3110-20. doi: 10.1007/s12094-024-03813-w.
28. Vinu W, Dr. Purnendu Kumar P, Mr. Katam Naga L, Dr. Ripon B, Dilip Kumar B, Bhaskar Jyoti C, et al. Ethical implications of artificial intelligence in healthcare decision-making a crossroads of social values, computer algorithms, and medical practice. JNS & History, politics, culture 2023;35:2371-97. doi: 10.59670/jns.v35i.3993.
29. Raza S, Shaban-Nejad A, Dolatabadi E, Mamiya H. Exploring bias and prediction metrics to characterise the fairness of machine learning for equity-centered public health decision-making: A narrative review. IEEE Access 2024;12:180815-29. doi: 10.1109/access.2024.3509353.
30. Leiden University Medical Center. Optimodel [Internet]. Leiden: LUMC. Available at: https://apps.apple.com/tr/app/optimodel/id1235461963. 2025. [Accessed: 28.02.2025]
31. Forsberg JA, Wedin R, Boland PJ, Healey JH. Can we estimate short- and intermediate-term survival in patients undergoing surgery for metastatic bone disease? Clin Orthop Relat Res 2017;475:1252-61. doi: 10.1007/s11999-016-5187-3.
32. Yu W, Chen D, Ding X, Qiao L, Zhang L, Gao X, et al. A critical appraisal of clinical practice guidelines on surgical treatments for spinal metastasis. Eur Spine J 2024;33:1868-98. doi: 10.1007/s00586-023-08127-z.
33. Brown JE, Wood SL, Confavreux C, Abe M, Weilbaecher K, Hadji P, et al. Management of bone metastasis and cancer treatment-induced bone loss during the COVID-19 pandemic: An international perspective and recommendations. J Bone Oncol 2021;29:100375. doi: 10.1016/j.jbo.2021.100375.