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Time series based forecasting of ankle and foot soft tissue injuries in Mongolia via Sarima and changepoint aware models

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Objective: Ankle and foot soft tissue injuries impose a substantial burden on emergency healthcare services, particularly in low- and middle-income countries where injury surveillance systems remain limited. This study aimed to investigate temporal trends and seasonal patterns of ankle and foot soft tissue injuries in Mongolia and to forecast future incidence using time-series models. **Methods:** Emergency department records from the National Trauma and Orthopedic Research Center of Mongolia (2014–2023) were retrospectively analyzed. Monthly ankle and foot soft tissue injury cases were aggregated and evaluated using descriptive statistics and chi-square tests. Seasonal autoregressive integrated moving average (SARIMA) models were applied to assess temporal trends and seasonal variation. Model performance and forecast accuracy were evaluated using AIC, BIC, residual diagnostics, and MAPE. **Results:** A total of 45,237 cases were identified during the study period. The majority of injuries occurred among males (54.5%) and residents of Ulaanbaatar (86.0%) ($p < 0.001$). Clear seasonal variation was observed, with injury peaks during winter and late spring. Among the candidate models, SARIMA (2,1,10)(1,1,1)12 demonstrated the best fit. Forecast validation showed acceptable predictive accuracy (MAPE = 19.43%). Projections for 2024–2025 indicated a relatively stable injury burden with persistent seasonal fluctuations. **Conclusions:** Ankle and foot soft tissue injuries in Mongolia demonstrate distinct temporal and seasonal patterns. SARIMA modeling provides a practical approach for forecasting injury trends and may facilitate seasonal injury surveillance, targeted prevention programs, and evidence-based healthcare resource allocation.

Keywords: Ankle injury; Foot injury; Time-series analysis; SARIMA; Seasonal variation; Injury epidemiology

Introduction

Ankle injuries represent a substantial source of musculoskeletal morbidity, work-related disability, and long-term functional impairment worldwide, affecting populations across high, middle, and low-income countries.[1,2] Clinically, these injuries refer to structural damage to the bones, ligaments, tendons, cartilage, or surrounding soft tissues of the ankle joint resulting from mechanical loading, torsional stress, or direct trauma. These injuries frequently manifest as pain, swelling, and functional limitation and may lead to persistent instability or chronic disability if not adequately managed.[3,4] In particular, repeated or poorly treated ankle injuries may progress to chronic lateral ankle instability (CLAI), recurrent sprains, persistent pain, and secondary osteochondral lesions, thereby significantly impairing mobility, work productivity, and quality of life.[5]

The etiology and risk factors of ankle injuries have been extensively investigated. Sudden directional changes during sports participation, improper landing mechanics, uneven playing surfaces, and insufficient use of protective equipment are among the most frequently reported causes.[2,3] Additional contributing factors include abrupt inversion or rotational movements, excessive mechanical loading, muscular fatigue, impaired balance control, ligamentous laxity, and a prior history of ankle injury.[6,7] Neuromuscular fatigue may further compromise joint stability by disrupting proprioceptive control and coordinated muscle activation, thereby increasing susceptibility to injury during high intensity physical activities.[8]

In many Asian countries, including those in East and Central Asia, ankle injury epidemiology is strongly influenced by sports culture and environmental conditions.[9] High participation in activities involving frequent running, jumping, and pivoting such as wrestling and martial arts places substantial torsional stress on the ankle joint, thereby elevating injury risk.[10] In Mongolia, several contextual factors uniquely contribute to the burden of ankle injuries. Traditional sports practiced during the Naadam festival, particularly Mongolian wrestling, involve repetitive pivoting movements, abrupt weight transfer, and falls on a single supporting limb, generating considerable mechanical stress on ankle ligaments and articular structures. The limited use of protective equipment in traditional sports may further increase injury susceptibility.[11,12]

Environmental conditions also play an important role. Mongolia's extreme continental climate, characterized by pronounced seasonal variation, contributes to a higher incidence of ankle injuries during winter months. Icy and slippery surfaces increase the risk of ankle sprains and falls not only during sports activities but also during routine daily activities, creating a distinct seasonal pattern of injury occurrence. Furthermore, the use of non-specialized or substandard indoor sports facilities, including uneven flooring and inadequate surface materials, represents an additional risk factor in Mongolia and other Asian countries.[12,13]

Given the heterogeneous distribution and pronounced seasonal variation of ankle injuries, systematic quantitative analysis of temporal patterns is essential. Although ankle injuries demonstrate apparent seasonal trends, these patterns are influenced by multiple interacting factors, including climate variability, population mobility, and behavioral changes.[14] Therefore, simple descriptive or deterministic approaches are insufficient to capture temporal dependence, autocorrelation, and stochastic variation in injury occurrence. Time-series analysis provides a robust statistical framework for modeling such complex temporal dynamics and enables more accurate forecasting of injury trends. The Box–Jenkins methodology provides a classical framework for time-series modeling, including model identification, estimation, and diagnostic validation using autoregressive integrated moving average (ARIMA) models.[15] However, when strong seasonal patterns are present, seasonal extensions such as the Seasonal Autoregressive Integrated Moving Average (SARIMA) model are more appropriate, as they explicitly account for periodic fluctuations in the data. In the present study, clear annual seasonality ($s = 12$) was observed in monthly injury counts, supporting the use of SARIMA over non-seasonal ARIMA models.[16]

Traditional regression models are often limited in their ability to account for temporal dependence and autocorrelation inherent in longitudinal injury data. In contrast, time-series approaches such as ARIMA and SARIMA models have increasingly been applied in epidemiological research to evaluate temporal trends and generate forecasts. These models provide a more rigorous and data-driven framework for understanding seasonal injury patterns and can support evidence-based decision-making in healthcare resource allocation and injury prevention strategies.[17] Therefore, the objective of this study was to (1) analyze temporal trends and seasonal patterns of ankle and foot soft tissue injuries in Mongolia and (2) develop and validate a SARIMA model to forecast future injury counts. While the Box–Jenkins framework using ARIMA models is widely applied in time-series analysis, it does not explicitly account for seasonal variation. In contrast, SARIMA models incorporate seasonal components and have been shown to provide superior performance in datasets with clear periodic patterns, particularly in epidemiological and healthcare forecasting studies.[18]

Material and Methods

Data Source and Study Population

This study utilized routinely collected emergency department data from the National Center for Traumatology and Orthopedics (NCTO), the largest tertiary trauma referral hospital in Mongolia, covering the period from January 2014 to December 2023. The dataset included patient demographics (age and sex), clinical diagnoses, and recorded mechanisms of injury. Ankle and foot soft tissue injuries were identified using the International Classification of Diseases, 10th Revision (ICD-10), specifically codes related to ligament and tendon injuries at the ankle and foot level (S93.4–S93.6 and S96.0–S96.9). Only newly diagnosed traumatic injuries were included in the analysis. The unit of analysis was unique patient encounters. To avoid duplicate counting, repeated visits related to the same injury episode were excluded using patient identification numbers, visit dates, and diagnostic codes. Records with missing key variables were removed during data cleaning. Eligible cases were aggregated by month, resulting in 120 consecutive monthly observations, which were structured as a time-series dataset for statistical analysis and forecasting.

Descriptive and Inferential Statistical Analysis

Descriptive statistics were used to summarize patient demographic and clinical characteristics. Categorical variables, including age group, sex, diagnosis category, and injury mechanism, were presented as frequencies and percentages. Differences in the distribution of ankle and foot injuries across these categories were assessed using the chi-square (x^2) test. A *p*-value of <0.05 was considered statistically significant. All descriptive and inferential analyses were conducted using Stata version 17 (StataCorp, College Station, TX, USA).

Time-Series Modeling Approach

Given the temporal dependence and seasonal variability inherent in monthly injury data, a Seasonal Autoregressive Integrated Moving Average (SARIMA) model was employed to analyze temporal trends and forecast future injury counts. Time-series modeling was conducted using R statistical software (R Foundation for Statistical Computing, Vienna, Austria). The general SARIMA model is expressed as SARIMA (p, d, q)(P, D, Q)_s, where (p, d, q) represent the non-seasonal autoregressive (AR), differencing (I), and moving average (MA) orders, and (P, D, Q) represent the corresponding seasonal parameters. The parameter s denotes the length of the seasonal cycle. Because the dataset consisted of monthly observations, the seasonal period was set to s = 12, representing annual seasonality in injury counts.

Time-Series Preprocessing and Stationarity Assessment

Prior to model fitting, the time series of monthly ankle and foot soft tissue injury counts was assessed for stationarity. Stationarity is a key assumption of SARIMA models and requires that the statistical properties of the series, including mean and variance, remain constant over time. If the original series exhibited trends or seasonal fluctuations, appropriate differencing procedures were applied to achieve stationarity. Non-seasonal differencing was used to remove long-term trends, while seasonal differencing with a lag of 12 months was applied to account for annual seasonal variation. When both trend and seasonal components were present, non-seasonal and seasonal differencing were applied simultaneously to stabilize the series prior to model identification and estimation.

Model Specification

The SARIMA model was specified to capture both non-seasonal and seasonal dynamics in the monthly injury time series. Model orders (p, d, q) and (P, D, Q)_s were determined based on the temporal structure of the data, with the seasonal period fixed at s = 12 due to the monthly frequency of observations.

Parameter Estimation

Model parameters were estimated using maximum likelihood estimation (MLE). The estimated coefficients included non-seasonal autoregressive and moving average parameters, seasonal autoregressive and moving average parameters, and the variance of the model error term.

Model Identification and Selection

Preliminary model identification was conducted using autocorrelation function (ACF) and partial autocorrelation function (PACF) plots to evaluate temporal dependence and seasonal structure. Multiple candidate SARIMA models were fitted and compared using the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC).

Models with lower AIC and BIC values were considered to provide a better balance between model fit and complexity. The final model was selected based on the minimum information criteria values.

Residual Diagnostics

Model adequacy was evaluated by examining the residual series, defined as the difference between observed and fitted values. For a well-specified model, residuals are expected to behave as white noise with no significant autocorrelation. Residual independence was formally assessed using the Ljung–Box test, where a p-value greater than 0.05 indicates no significant autocorrelation.

Forecasting and Model Evaluation

Future injury counts were forecast using the fitted SARIMA model. For model validation, data from January 2014 to December 2022 were used for model training, while data from January to December 2023 were reserved as a holdout test set for out-of-sample evaluation. Forecast accuracy was assessed using Mean Absolute Percentage Error (MAPE) and Theil's U1 statistic. MAPE provides an intuitive measure of average percentage prediction error, while Theil's U1 evaluates forecasting performance relative to a naïve benchmark model. Lower MAPE values and smaller U1 statistics indicate better predictive performance. Prediction accuracy was additionally calculated as (100 – MAPE) (%), providing an interpretable measure of forecasting reliability.

Ethical Statements

This study was approved by the Research Ethics Committee of the Mongolian National University of Medical Sciences (MNUMS) (Approval No. 2024/3-06; June 14, 2024) and by the National Trauma and Orthopedic Research Center (NTORC), Mongolia. As this study utilized retrospectively collected and anonymized routinely recorded clinical data, the requirement for informed consent was waived by the ethics committees. The study was conducted in accordance with the principles of the Declaration of Helsinki.

Results

Descriptive Overview of Injury Patterns

During the study period (2014–2023), a total of 45,237 cases of ankle and foot soft tissue injuries were recorded. Monthly injury counts demonstrated a clear seasonal pattern throughout the observation period. The lowest mean monthly counts were observed in February (291 cases), followed by January (357.5 cases). Injury counts remained relatively stable during the first quarter of the year and mid-summer months. Higher injury frequencies were observed from September to December, with mean monthly values ranging between 335.5 and 421.5 cases.

The relative difference between the highest (July) and lowest (February) mean monthly counts was approximately 44.8%, indicating marked seasonal variation. Boxplot analysis demonstrated variability across months, with outliers observed in July, August, and November (Fig.1). Injury occurrence also varied by day of the week, with higher frequencies observed on Sundays, Mondays, and Saturdays (Fig.2).

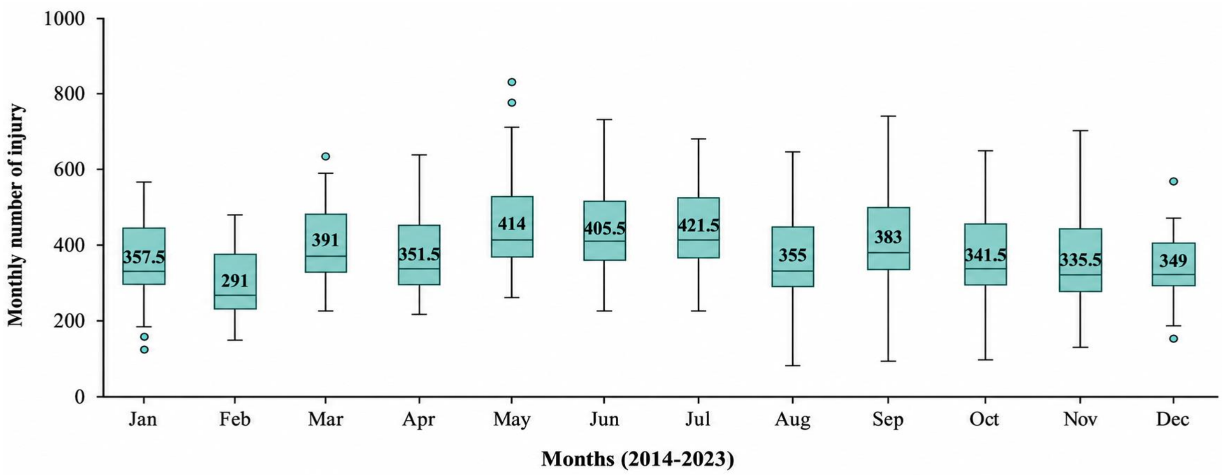

Figure 1. Box-plot with data on foot and ankle ligament injury by days (2014-2023).

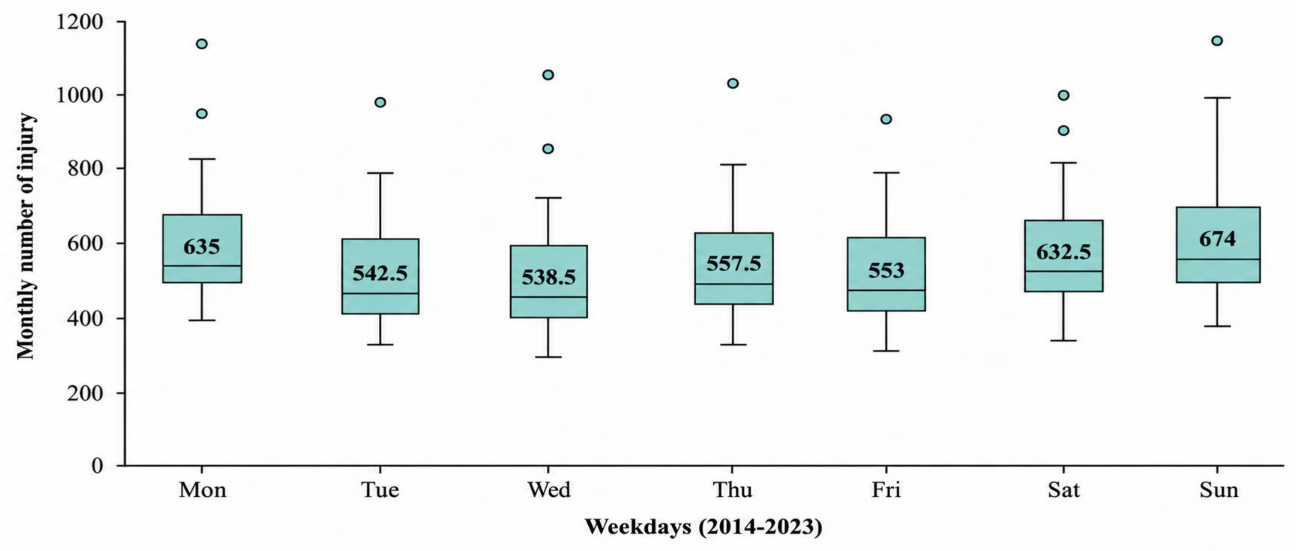

Figure 2. Box-plot with data on foot and ankle ligament injury by days (2014-2023)

Temporal Structure of the Time Series

Figure 3 presents the monthly time series of ankle and foot soft tissue injuries from 2014 to 2023. The series shows recurrent peaks and troughs, consistent with seasonal variation across years. The Augmented Dickey–Fuller (ADF) test confirmed stationarity after differencing (test statistic = –4.5903, $p = 0.01$), indicating that the processed time series met the assumptions required for SARIMA modeling (Table 1).

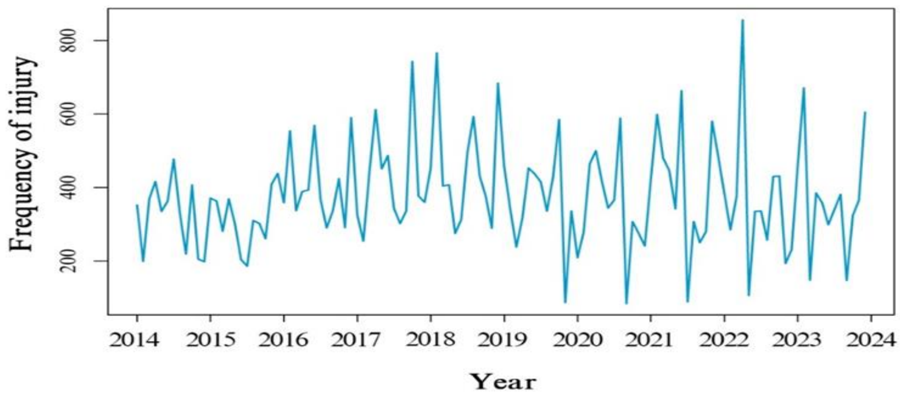

Figure 3. Time series plot of foot and ankle ligament injury cases from (2014-2023)

Table 1. ADF test for Level Stationarity.

Test	Statistics	Lag Order	*p*-value
ADF	-4.5903	4	0.01

ADF-Augmented Dickey-Fuller, p value was defined by Chi square test

Model Identification and Selection

Autocorrelation Function (ACF) and Partial Autocorrelation Function (PACF) plots of the differenced series were examined to guide model identification (Fig. 4). The ACF plot showed significant autocorrelation at lag 1 with gradual decay, while the PACF plot demonstrated several significant partial autocorrelations at early lags, indicating the presence of both autoregressive and moving-average components. Multiple candidate SARIMA models were fitted and compared using the Akaike Information Criterion

(AIC), corrected AIC (AICc), and Bayesian Information Criterion (BIC). Among the evaluated models, SARIMA $(2,1,10) \times (1,1,1)_{12}$ yielded the lowest information criteria values (AIC = 1358.14; AICc = 1351.50; BIC = 1397.08) and was therefore selected as the optimal model (Table 2).

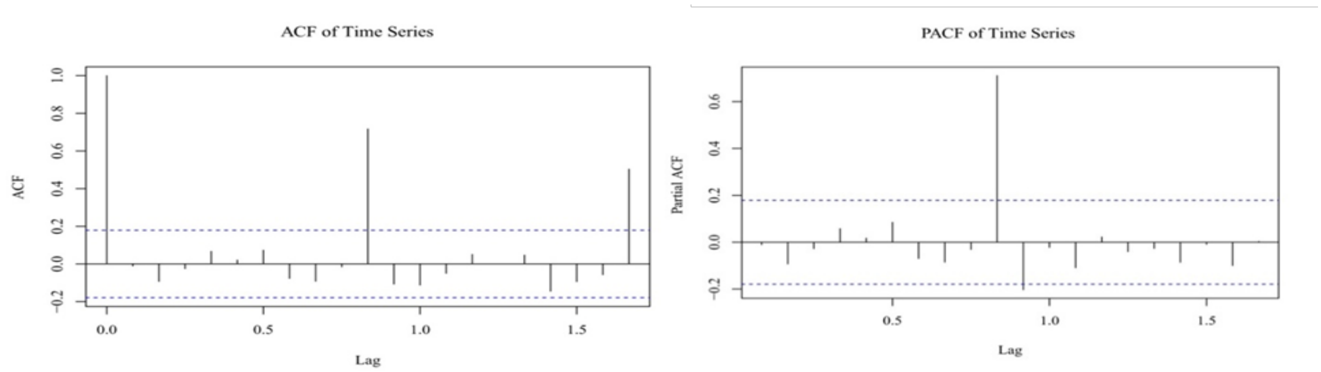

Figure 4. **Plot of the ACF and PACF of First Difference foot and ankle ligament injury cases. (a) ACF of differenced foot and ankle ligament injury cases, (b) PACF of differenced foot and ankle ligament injury cases**

Table 2. Potential SARIMA models with their AIC, AICc and BIC values.

SARIMA Models	AIC	AICc	BIC
SARIMA $(1, 1, 1) \times (1, 1, 1)_{12}$	1394.83	1395.42	1408.19
SARIMA $(1, 0, 1) \times (1, 1, 1)_{12}$	1398.38	1398.97	1411.79
SARIMA $(1, 1, 1) \times (1, 1, 0)_{12}$	1424.32	1424.71	1435.01
SARIMA $(2, 1, 3) \times (1, 1, 1)_{12}$	1389.43	1390.9	1410.81
SARIMA $(3, 1, 3) \times (1, 1, 1)_{12}$	1391.28	1393.14	1415.34
SARIMA $(2, 1, 5) \times (1, 1, 1)_{12}$	1384.76	1387.05	1411.49
SARIMA $(2, 1, 7) \times (1, 1, 1)_{12}$	1380.83	1384.15	1412.91
SARIMA $(2, 1, 9) \times (1, 1, 1)_{12}$	1376.5	1381.06	1413.92
SARIMA $(2, 1, 10) \times (1, 1, 1)_{12}$	1358.14	1363.42	1398.23

SARIMA- Seasonal Autoregressive Integrated Moving Average, AIC-Akaike Information Criterion, AICc- corrected Akaike Information Criterion, BIC-Bayesian Information Criterion

Model Diagnostics and Forecasting Performance

Diagnostic evaluation indicated that the fitted model adequately captured the temporal structure of the data. The Ljung–Box test yielded a *p*-value of 0.8, indicating no significant residual autocorrelation and confirming that the residuals behaved as white noise (Table 3). Residual ACF and PACF plots also showed no systematic temporal dependence (Fig. 5).

For validation, data from 2014–2022 were used for model training, while 2023 served as the holdout period. Specifically, the model demonstrated a mean absolute error (MAE) of 68.21, a root mean square error (RMSE) of 94.00, and a mean absolute percentage error (MAPE) of 24.15% (Table 4).

The SARIMA-based time-series forecast of monthly ankle and foot soft-tissue injury cases is shown in (Fig. 6). The observed data from 2014 to 2023 demonstrate notable temporal fluctuations with several intermittent peaks throughout the study period. Despite this variability, the overall pattern suggests a relatively stable baseline level of injury occurrence. The fitted SARIMA model predicts that the number of injury cases will remain relatively stable in the upcoming years, with moderate fluctuations around the estimated mean. The widening prediction intervals over time reflect increasing uncertainty in longer-term forecasts. These findings indicate that the SARIMA model adequately captures the temporal dynamics of injury occurrence and provides a useful framework for anticipating future trends. The temporal trend and forecasts of ankle and foot soft-tissue injury cases are shown in (Fig. 7). The observed data from 2014 to 2023 demonstrate noticeable variability, with two structural changes identified around 2019 and 2021. Following a temporary decline during 2020–2021, the number of injury cases increased again toward 2023.

Table 3. Ljung-Box test of SARIMA (2, 1, 10) × $(1, 1, 1)_{12}$

Test	Statistics	*p*-value
Ljung-Box	16.256	0.1798

p value was defined by Chi square test

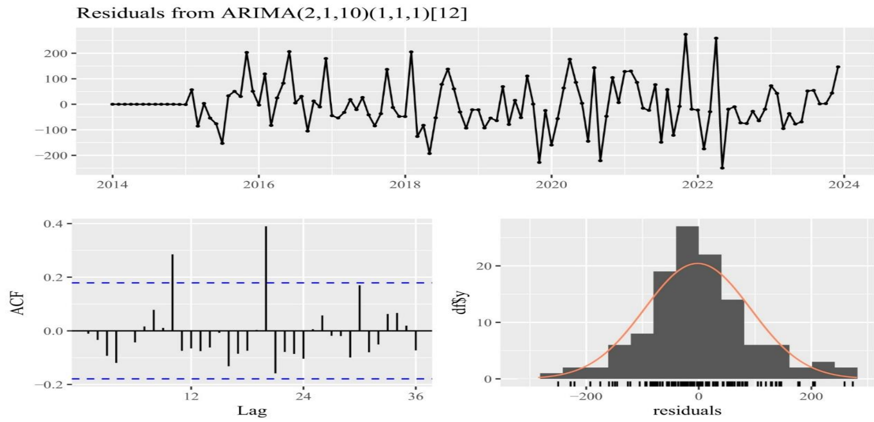

Figure 5. "Residual diagnostics (ACF/PACF of residuals)"

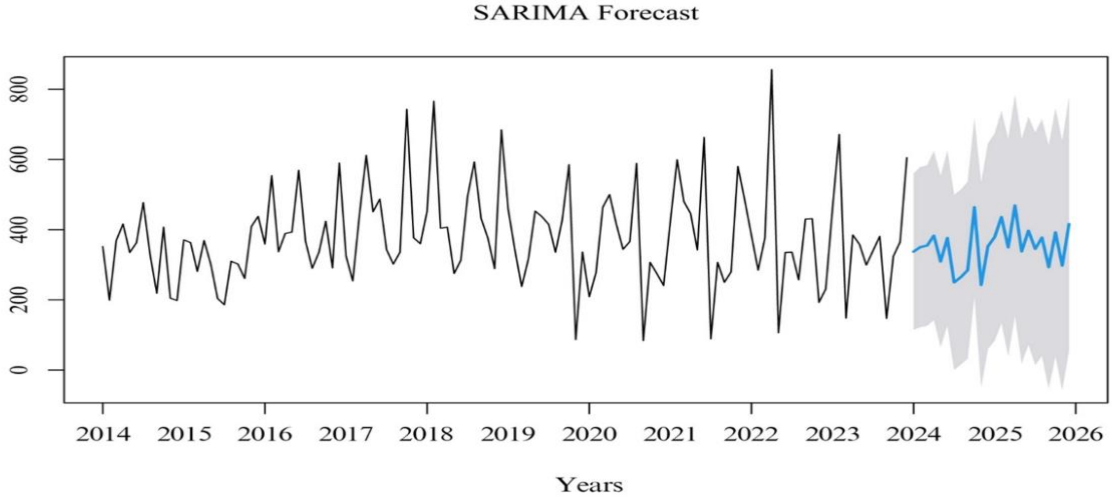

Figure 6. Plot of Forecasted values of SARIMA (2,1,10) × (1,1,1)12 model with 95% confidence limits

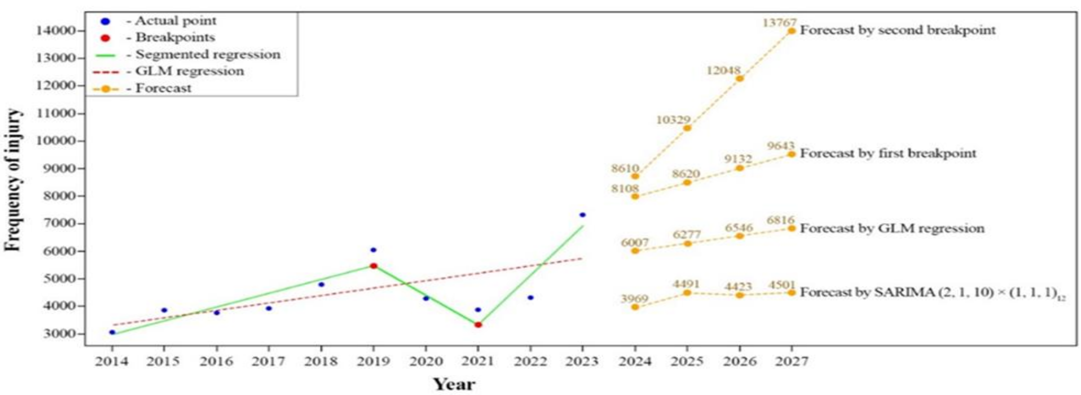

Figure 7. Observed and Forecasted Annual Frequency of Ankle and Foot Injuries Using Segmented Regression, GLM, and SARIMA Models (2014–2027).

Forecasts generated using different modelling approaches reveal varying trajectories. Breakpoint-based and segmented regression models suggest a steeper increase in future injury incidence, whereas the SARIMA model predicts a relatively stable trend with moderate fluctuations. These findings indicate that the SARIMA model provides a more conservative estimate of future injury patterns.

Table 4. Out of sample Validation for SARIMA (2, 1, 10) × (1, 1, 1)12 with Forecast Performance Statistics.

Year	Month	Forecast value	Lo 95	Hi 95
2024	Jan	337.5	115.0	560.0
2024	Feb	350.4	122.1	578.6
2024	Mar	354.5	126.3	582.8
2024	Apr	383.2	142.9	623.4
2024	May	309.3	66.5	552.1
2024	Jun	376.0	127.7	624.4
2024	Jul	249.8	0.9	498.8
2024	Aug	264.9	16.0	513.8
2024	Sep	284.6	32.8	536.3
2024	Oct	463.9	211.8	715.9
2024	Nov	242.5	47.8	532.8
2024	Dec	352.6	60.3	644.9
2025	Jan	379.1	84.2	673.9
2025	Feb	436.0	134.6	737.5
2025	Mar	349.7	41.5	657.9
2025	Apr	468.9	155.7	782.2
2025	May	338.0	18.9	657.1
2025	Jun	397.1	72.8	721.5
2025	Jul	345.3	14.8	675.7
2025	Aug	377.4	40.3	714.6
2025	Sep	293.1	51.8	638.0
2025	Oct	392.3	40.4	744.2
2025	Nov	297.8	56.8	652.4
2025	Dec	415.9	55.9	775.9
Metric Value				
MAE- 68.21				
RMSE- 94.00				
MAPE- 24.15%				

MAE Mean Absolute Error, *RMSE-Root Mean Square Error, MAPE- Mean Absolute Percentage Error*

Discussion

This study provides a comprehensive time-series analysis of ankle and foot soft tissue injuries in Mongolia over a ten-year period. The findings demonstrate clear temporal and seasonal patterns in injury counts and confirm the suitability of SARIMA modeling for forecasting injury trends in a low- and middle-income country setting. These results highlight the value of time-series approaches for quantifying temporal dependence and supporting evidence-based healthcare planning.[19,20]

The observed male predominance and higher injury burden among urban residents are consistent with previous epidemiological studies from Asia, Europe, and North America. Higher injury rates among males have been attributed to greater participation in physically demanding occupations and high-intensity sports involving rapid directional changes and repetitive loading. Similarly, urban populations may have increased exposure to organized sports, recreational activities, and higher mobility, contributing to elevated injury counts observed in this study.[21]

A key finding of this analysis is the pronounced seasonal variation in injury counts. Peaks observed during winter months are likely associated with icy surfaces, reduced traction, and impaired balance, which increase the risk of falls and ankle sprains. Secondary peaks during late summer and early autumn may correspond to increased outdoor activities and sports participation. Similar seasonal distributions have been reported in studies conducted in temperate and continental climates, emphasizing the influence of environmental and behavioral factors on injury patterns.[22,23]

Mongolia's unique environmental and cultural context may further amplify these trends. The country's prolonged winters and extreme climatic conditions likely contribute to increased fall-related injuries. In addition, traditional Mongolian wrestling, particularly during the Naadam festival, involves repetitive pivoting, abrupt weight shifts, and single-leg loading, all of which impose substantial biomechanical stress on the ankle joint. The absence of standardized protective equipment in these activities may further contribute to seasonal increases in injury counts.[24,25]

From a methodological perspective, the SARIMA model demonstrated satisfactory performance in capturing both seasonal dependence and temporal autocorrelation in the injury data. Although ankle injuries exhibit visually apparent seasonal patterns, time-series modeling provides a more rigorous quantitative framework by accounting for autocorrelation, stochastic variability, and dynamic temporal structures that cannot be fully captured by descriptive approaches alone. The forecasting results suggest that seasonal injury patterns are likely to persist, highlighting the potential role of predictive modeling in healthcare resource allocation and targeted injury-prevention strategies.[26]

These findings have important practical implications. Seasonal forecasting of injury counts may support hospital preparedness, optimize staffing and resource allocation, and inform the timing of public health interventions. In particular, targeted winter injury-prevention programs, including fall-prevention campaigns and environmental safety measures, may reduce injury burden. Additionally, increased awareness and preventive strategies during peak sports seasons may further mitigate risk.[27]

Several limitations should be acknowledged. First, the analysis was based on data from a single tertiary referral center, which may limit generalizability to the broader population. Second, individual-level exposure variables, such as sports participation intensity, occupational risk, and meteorological data, were not available. Third, the study relied on routinely collected administrative data, which may be subject to coding inaccuracies. Future studies incorporating multi-center datasets and environmental variables may further improve predictive accuracy and strengthen injury prevention strategies.[28,29]

Despite these limitations, this study demonstrates that time-series modeling offers a robust framework for analyzing and forecasting injury patterns. The integration of such models into injury surveillance systems may enhance data driven decision making and improve public health outcomes.[30]

Conclusion

This study provides the first comprehensive epidemiological evidence on foot and ankle soft tissue injuries in Mongolia, revealing clear seasonal patterns driven by climatic and behavioral factors. The findings highlight the importance of targeted winter injury-prevention strategies and data-driven public health policies to reduce the growing burden of musculoskeletal trauma in cold-climate populations.

Conflict of Interest

The authors declare that there are no conflicts of interest that could be perceived as influencing the research reported in this manuscript. None of the authors have received any financial support, grants, consulting fees, honoraria, stock ownership, or other forms of compensation from any commercial or non-commercial entities that may have an interest in the subject matter or materials discussed in this article.

Moreover, the authors confirm that there are no non-financial competing interests, such as personal relationships, academic commitments, institutional affiliations, or intellectual beliefs, that could have affected the objectivity, integrity, or transparency of the work presented.

All authors have contributed significantly to the study and have reviewed and approved the final version of the manuscript.

The authors collectively take full responsibility for the content, accuracy, and impartiality of the data and conclusions presented herein.

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