

Step width as a robust predictor of fall risk in patients with moderate-to-severe knee osteoarthritis: A gait-based prediction model

yao wang

Shanxi Medical University

Pengcui Li

lpc1977@163.com

Shanxi Medical University

Danni Ruan¹

Shanxi Medical University

Dahai Pang¹

Shanxi Medical University

Article

Keywords: Knee osteoarthritis, Fall risk, Step width, Gait analysis, Prediction model, Firth logistic regression

Posted Date: August 13th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10344489/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Step width as a robust predictor of fall risk in patients with moderate-to-severe knee osteoarthritis: A gait-based prediction model

Authors:

Yao Wang¹⁺, Pengcui Li*, Danni Ruan¹, Dahai Pang¹

Affiliations:

Orthopedic Laboratory of Shanxi Medical University Second Hospital, Shanxi Medical University, Taiyuan, China

Email addresses:

Yao Wang: 3314265383@qq.com

Danni Ruan: 202401932036@sxmu.edu.cn

Dahai Pang: 1254569239@qq.com

Corresponding author:

*Pengcui Li, Doctoral Professor

Orthopedic Laboratory of Shanxi Medical University Second Hospital, Shanxi Medical University, Taiyuan, China

Email: lpc1977@163.com

Abstract

Objective: Patients with knee osteoarthritis (KOA) have a significantly increased risk of falls, yet the relationship between gait parameters and fall risk in moderate-to-severe KOA remains unclear. This study aimed to identify independent gait predictors of falls and develop a simple clinical screening tool. **Methods:** A total of 120 patients with Kellgren–Lawrence grade III–IV KOA (60 fallers, 60 non-fallers) were enrolled. Spatiotemporal, kinetic, and kinematic parameters were collected using the Footscan® plantar pressure system. Lasso regression with 10-fold cross-validation was used for variable selection, and Firth penalized-likelihood logistic regression was applied to address complete separation. Model stability was evaluated by bootstrap internal validation (1000 resamples) and leave-one-out cross-validation (LOOCV), with clinical utility assessed via decision curve analysis (DCA). **Results:** Mean step width emerged as the sole independent predictor of falls (univariate Firth regression: OR = 2.24, 95% CI: 1.58–3.91, $P < 0.001$). The model demonstrated excellent discriminative ability (LOOCV AUC = 0.956, accuracy = 95.8%, sensitivity = 100%, specificity = 91.7%), with 100% sign consistency in bootstrap validation. A threshold of mean step width > 18 cm effectively identified high-risk individuals. DCA confirmed a positive net benefit across clinically relevant threshold

probabilities.**Conclusion:** Mean step width is a robust, low-cost gait-based predictor of fall risk in moderate-to-severe KOA. The proposed threshold of > 18 cm enables rapid clinical screening and community-based risk stratification.

Keywords: Knee osteoarthritis; Fall risk; Step width; Gait analysis; Prediction model; Firth logistic regression

1 Introduction

Knee osteoarthritis (KOA) is a common degenerative joint disease affecting hundreds of millions of people worldwide, particularly the middle-aged and elderly populations. With the increasing aging of the population, the prevalence of KOA continues to rise, making it an important public health issue[1]. Patients with KOA not only suffer from chronic pain and functional impairment but also face a significantly increased risk of falls. Studies have shown that the incidence of falls in KOA patients is 2–3 times higher than that in healthy peers, with approximately 40–60% of KOA patients experiencing at least one fall per year[2]. Falls in KOA patients can lead to fractures, soft tissue injuries, further decline in mobility, reduced quality of life, and even increased mortality risk[3]. Gait abnormalities are typical manifestations of KOA, including reduced gait speed, shortened step length, prolonged stance phase, and limited joint range of motion[4]. These gait changes are both pathological consequences of KOA and may increase fall risk by affecting balance control and postural stability. In recent years, the development and popularization of gait analysis technology have made it possible to objectively and quantitatively evaluate gait abnormalities. Plantar pressure gait analysis systems can accurately collect spatiotemporal, kinetic, and kinematic parameters, providing technical support for studying the relationship between gait and falls. Currently, research on the correlation between gait parameters and fall risk in KOA patients is still insufficient, particularly for patients with moderate-to-severe KOA. Because of more severe joint structure damage and more pronounced pain, patients with moderate-to-severe KOA may have more prominent gait abnormalities and fall risk. However, simple, low-cost, and generalizable gait-based fall risk prediction tools specifically for moderate-to-severe KOA patients are lacking. This study aimed to: (1) compare gait parameters between patients with moderate-to-severe KOA with and without a history of falls; (2) analyze the correlation between gait parameters and fall risk and identify independent risk factors; and (3) develop a simple and reliable clinical prediction tool to provide an objective basis for fall risk assessment in patients with moderate-to-severe KOA.

2 Methods

2.1 Study participants

This study was designed as an observational cross-sectional study and did not involve any intervention or randomization, thus clinical trial registration was not required. Using a convenience sampling method, patients with KOA were recruited from the orthopedic outpatient and inpatient departments of a tertiary hospital between March 2022 and December 2023. A total of 120 patients were enrolled in this study, including 60 in the fall group and 60 in the non-fall group.

Inclusion criteria: (1) met the American College of Rheumatology diagnostic criteria for KOA; (2) Kellgren-Lawrence (K-L) grade III–IV (moderate-to-severe); (3) age 50–85 years; (4) able to walk independently for at least 10 meters (assistive devices permitted); (5) provided informed consent and voluntarily participated in this study.

Exclusion criteria: (1) other types of arthritis (e.g., rheumatoid arthritis, gouty arthritis); (2) history of knee replacement surgery; (3) severe neurological diseases (e.g. Parkinson's disease, stroke sequelae) affecting walking function; (4) severe cardiopulmonary disease precluding gait testing; (5) cognitive impairment preventing completion of testing; (6) acute lower limb injury or acute exacerbation of pain. Based on whether participants had experienced a fall in the past year, they were divided into a fall group and a non-fall group. A fall was defined as "an unintentional event resulting in loss of balance and descent to the ground or a lower level"[5-8].

2.2 General data collection

A standardized questionnaire was used to collect the following information: (1) demographic characteristics: age, sex, height, weight, with body mass index (BMI) calculated as weight (kg)/height² (m²); (2) clinical characteristics: K-L grade (III/IV), disease duration; (3) fall-related factors: history of falls in the past year (yes/no), number of falls, assistive device use, chronic disease history (hypertension/diabetes/stroke), medication use, visual status, cognitive impairment, fear of falling, and environmental factors. Ethical approval for this study was obtained from the hospital ethics committee (approval number: (2026) YX No. 207). Written informed consent was obtained from all participants.

2.3 Gait parameter acquisition

Gait parameters were collected using the Footscan® plantar pressure gait analysis system (RSscan International, Belgium)[8]. The system consists of a 2-meter pressure plate (sampling frequency 500 Hz), data acquisition unit, and analysis software. This system has been demonstrated to have good reliability and validity[9-11]. Testing procedure: (1) before testing, participants were explained the testing procedure and allowed to practice walking; (2) participants walked barefoot on the pressure plate at their natural walking speed, with each foot making complete contact counted as one valid trial; (3) three valid trials were collected for each participant, and the average values were used for analysis; (4) a professional was present for protection during testing to prevent falls. All tests were conducted under uniform lighting, on a flat surface, with ambient noise controlled at < 40dB.

Gait parameters collected included:

Kinetic parameters: static left/right forefoot/hindfoot weight-bearing ratio (%), dynamic left/right foot force ratio, left/right impulse, left/right foot contact area (cm²), left/right foot progression angle (°).

Kinematic parameters: left/right hip range of motion (°), hip maximum/minimum values (°), left/right knee range of motion (°), knee maximum/minimum values (°), left/right ankle range of motion (°), ankle maximum/minimum values (°).

2.4 Quality control

(1)Data acquisition was performed by two researchers who had undergone unified training to ensure standardization of procedures; (2) before gait testing, equipment calibration status was checked to ensure data accuracy; (3)data entry was performed independently by two individuals with cross-checking; (4) outliers were verified against original records and excluded if necessary.

2.5 Statistical analysis

Statistical analyses were performed using R software (version 4.3.1, R Foundation for Statistical Computing, Austria). Continuous variables were first tested for normality using the Shapiro-Wilk test. Normally distributed variables were expressed as mean±standard deviation (Mean±SD), and group comparisons were performed using independent samples t-tests (with homogeneity of variance assessed by Levene's test). Non-normally distributed variables were expressed as median (interquartile range), and group comparisons were performed using the Mann-Whitney U test. Categorical variables were expressed as frequency (percentage), and group comparisons were performed using the chi-square test or Fisher's exact test[12-13].To evaluate the main and interaction effects of knee osteoarthritis severity (K-L grade: III vs. IV) and fall history (yes vs no) on gait parameters, two-way ANOVA was performed. Univariate logistic regression was used to preliminarily screen gait parameters associated with fall risk. To avoid multicollinearity and identify core predictive variables, Lasso (least absolute shrinkage and selection operator) regression with 10-fold cross-validation was further employed for variable selection, using the "one-standard-error rule" to determine the optimal penalty parameter λ [14].Because complete separation in step width was observed between the fall and non-fall groups, rendering maximum likelihood estimation for ordinary logistic regression invalid, multivariate Firth penalized-likelihood logistic regression was used to estimate the independent effect of each variable on fall risk, calculating odds ratios (OR) and 95% confidence intervals (CI). Model stability was assessed using bootstrap internal validation (1000 resamples with replacement), calculating the sign consistency of regression coefficients for each variable and the 95% CI of the bootstrap AUC[15]. Leave-one-out cross-validation (LOOCV) was used to evaluate the generalizability of the model, calculating AUC, accuracy, sensitivity, and specificity[16]. Clinical utility was assessed using decision curve analysis (DCA), evaluating net benefit across different threshold probabilities[17].

2.6 Sample size calculation

Sample size was calculated using G*Power 3.1 software[18]. Based on pilot study results showing an effect size (Cohen's d) for gait speed between fall and non-fall groups of 0.65, with $\alpha = 0.05$ (two-sided) and power $(1-\beta) = 0.80$, and referencing previous KOA gait speed studies, the minimum required total sample size was calculated to be 102. Considering 10%

invalid data, the final sample size was determined to be 120 (60 in the fall group and 60 in the non-fall group).

3 Results

3.1 Comparison of Gait Parameters Between Fall and Non-Fall Groups in K-L Grade III and IV Patients

Based on Table 1, among patients with K-L grade III knee osteoarthritis, significant differences in multiple gait parameters were observed between the fall group (n=60) and the non-fall group (n = 60), suggesting that increased fall risk is closely associated with specific gait adaptation patterns[19-20]. Regarding joint range of motion, the left hip range (22.6° vs 31.4°, $P < 0.001$) and left knee maximum angle (52.05° vs 57.55°, $P = 0.0073$) were significantly smaller in the fall group than in the non-fall group. Additionally, the left knee range (35.5° vs 48.02°, $P < 0.001$) and right knee minimum angle (16.59° vs 10.65°, $P < 0.001$) also showed significant differences[21]. These findings indicate that patients in the fall group had greater restriction of hip and knee flexion-extension during walking, particularly inadequate knee extension (higher right knee min), which may reflect a "stiff" gait strategy adopted to increase joint stability due to pain or muscle weakness, at the expense of normal gait flexibility. In terms of static balance control, the static left anterior center of pressure value (22.47 vs 25.79, $P = 0.0145$) was significantly lower in the fall group, while the static right posterior value (31.05 vs 26.18, $P = 0.0183$) was significantly higher. This suggests that during static standing, the center of gravity in the fall group was shifted more posteriorly and to the right. Such asymmetric weight distribution may impair the ability to respond to sudden perturbations, thereby increasing the risk of instability. Dynamic plantar pressure testing showed that the dynamic left foot (680 vs 473.35, $P = 0.0326$) and dynamic right foot (658.35 vs 516.7, $P = 0.0006$) values were significantly higher in the fall group than in the non-fall group, indicating higher peak plantar pressure and more pronounced impact during walking in fall group patients, possibly related to poor landing control or compensatory exertion. Regarding spatiotemporal parameters, the fall group exhibited a typical "fall-risk gait": gait speed was significantly slower (0.4 m/s vs 0.58 m/s, $P < 0.001$); left and right step times were prolonged (725 ms vs 638 ms, $P = 0.0349$; 763 ms vs 650 ms, $P < 0.001$); and left/right step lengths and stride lengths were significantly shortened (e.g., left step length: 28.95 vs 38.85, $P = 0.0029$)[22-23]. Meanwhile, left single support time (316.7 vs 414.3, $P < 0.001$) was significantly shortened, while double support time (left double support: 938.55 vs 542.8, $P < 0.001$; right double support: 938.05 vs 558.35, $P < 0.001$) and total support time were significantly prolonged. These parameters collectively depict the gait characteristics of the fall group: small step length, low step frequency, and increased double support phase proportion. This represents a typical cautious, protective gait aimed at improving stability, but it consumes more energy and, due to reduced flexibility, may paradoxically increase fall risk. Furthermore, left step width (22.9 vs 8.85, $P < 0.001$) and right step width (22.96 vs 8.72, $P < 0.001$) were significantly greater in the fall group[24], along with an abnormally increased foot width (left foot width: 14.3 vs 8.45, $P < 0.001$). Clinically, patients in the fall group often adopt an "out-toeing" or widened base of support strategy, manifested as increased step width, while changes in plantar contact area may reflect altered foot landing

patterns. In summary, among patients with grade III osteoarthritis, the fall group exhibited a typical “high fall-risk gait pattern” characterized by decreased joint range of motion, slower gait speed, shorter step length, prolonged double support, and widened step width. These parameters may provide objective evidence for early identification of high-risk fall patients and for developing targeted intervention strategies.

Table 1 Comparison between the fall group and the non-fall group in patients with grade III osteoarthritis

Parameter	Fall Group	No Fall Group	Test	P
Left Hip Range	22.6 (15.4,31.27)	31.4 (27.98,38.15)	Mann–WhitneyU	<0.001
Left Hip Max	43.79±12.19	47.31±8.4	t 检验	0.1978
Left Hip Min	18.55 (11.2,23.6)	15.4 (9.83,22.6)	Mann–WhitneyU	0.3669
Right Hip Range	26.5 (21.4,31.4)	29.6 (25.83,32.1)	Mann–WhitneyU	0.0614
Right Hip Max	46.01±13.11	46.19±10.22	t 检验	0.9538
Right Hip Min	18.93±12.95	14.58±9.53	t 检验	0.1438
Left Knee Range	35.5±13.16	48.02±11.89	t 检验	<0.001
Left Knee Max	52.05 (47.6,56.45)	57.55 (52.62,64.27)	Mann–WhitneyU	0.0073
Left Knee Min	9.55 (6.22,25.2)	9.3 (6.05,14.6)	Mann–WhitneyU	0.4288
Right Knee Range	43.9 (29.1,50.9)	48.9 (37.45,53.05)	Mann–WhitneyU	0.1856
Right Knee Max	55.1 (51.8,66.1)	57.6 (49.6,62.3)	Mann–WhitneyU	0.9
Right Knee Min	16.59±6.94	10.65±5.91	t 检验	<0.001
Left Ankle Range	22 (17.6,26.7)	25.25 (23.02,28.98)	Mann–WhitneyU	0.07
Left Ankle Max	13.1 (7.5,18.23)	14.4 (12.95,17.15)	Mann–WhitneyU	0.2579
Left Ankle Min	10.75 (-13.1,-5.1)	-10.3 (-13.45,-6.17)	Mann–WhitneyU	0.9941
Right Ankle Range	20.4 (16.38,25.8)	20.9 (18.27,24.4)	Mann–WhitneyU	0.5842
Right Ankle Max	15.1(11.85,17.08)	13.35(10.33,17.12)	Mann–WhitneyU	0.2578
Right Ankle Min	-8.7 (-11.3,-0.68)	-7.3 (-11.35,-4.38)	Mann–WhitneyU	0.9234
Static Left Anterior	22.47±4.43	25.79±5.7	t 检验	0.0145
Static Left Posterior	27.78 (20.53,33.04)	28.9 (21.86,31.72)	Mann–WhitneyU	0.865
Static Right Anterior	19.27±4.3	20.65±3.76	t 检验	0.1911
Static Right Posterior	31.05(24.81,36.61)	26.18 (21.8,29.43)	Mann–WhitneyU	0.0183
Dynamic Left Foot	680 (466.7,760)	473.35(371.4,583.3)	Mann–WhitneyU	0.0326
Dynamic Right Foot	658.35(583.3,785.7)	516.7(444.6,600.08)	Mann–WhitneyU	<0.001

Left Foot Impulse	256.05(212.9,307.3)	265.6(204.45,319.75)	Mann–WhitneyU	0.8883
Right Foot Impulse	219.74±112.38)	190.72±82.63	t 检验	0.2592
Left Foot Contact Area	137.6(121.63,141.8)	136.65(120.4,154.7)	Mann–WhitneyU	0.3591
Right Foot Contact Area	126.8(85.72,135.4)	128.05(118.45,147.07)	Mann–WhitneyU	0.0932
Left Foot Progression Angle	17.82(14.8,22.17)	13.48 (10.63,20.65)	Mann–WhitneyU	0.0849

(Continued)Table 1 Comparison between the fall group and the non-fall group in patients with grade III osteoarthritis

Right Foot Progression Angle	17.2 (10.33,25.5)	17.85 (9.87,21.56)	Mann–WhitneyU	0.6099
Left Step Width	22.9 (22.15,23.4)	8.85 (5.75,10.65)	Mann–WhitneyU	<0.001
Right Step Width	22.96±1.85	8.72±3	t 检验	<0.001
Left Foot Width	14.3 (9.5,19)	8.45 (8,8.78)	Mann–WhitneyU	<0.001
Right Foot Width	14.14±6.44	7.79±1.12	t 检验	<0.001
Walking Speed	0.4±0.2	0.58±0.15	t 检验	<0.001
Left Step Time	725 (666.7,800)	638.05(614.3,716.7)	Mann–WhitneyU	0.0349
Right Step Time	763.35(683.3,1878.5)	650 (604.18,716.7)	Mann–WhitneyU	<0.001
Left Step Length	28.95 (16.98,36.55)	38.85 (30.88,46.12)	Mann–WhitneyU	0.0029
Right Step Length	35.05 (17.18,39.6)	38.9 (35.28,46.3)	Mann–WhitneyU	0.0319
Left Stride Length	57.1 (39.8,69.3)	75.05 (63.4,89)	Mann–WhitneyU	<0.001
Right Stride Length	57.1 (32.58,70.1)	74.7 (62.67,89.53)	Mann–WhitneyU	<0.001
Left Gait Cycle	1382.1(1087.47,1750)	1275(1228.5,1366.7)	Mann–WhitneyU	0.1667
Right Gait Cycle	1450(1229.15,1640)	1325(1235.67,1416.8)	Mann–WhitneyU	0.0656
Left Single Support	316.7 (285,350)	414.3(366.7,440.45)	Mann–WhitneyU	<0.001
Right Single Support	390(323.32,444.65)	400 (351.78,447.5)	Mann–WhitneyU	0.4195
Left Double Support	938.55(591.7,1575)	542.8(471.45,583.3)	Mann–WhitneyU	<0.001
Right Double Support	938.05(620.82,1000)	558.35(479.18,633.3)	Mann–WhitneyU	<0.001
Left Total Support	1173.35(945.8,1276.67)	921.35(827.42,1012.53)	Mann–WhitneyU	<0.001
Right Total Support	1280(987.53,1440.83)	958.35(866.7,1091.67)	Mann–WhitneyU	<0.001

Based on Table 2, among patients with K-L grade IV knee osteoarthritis, clear differences in gait strategy were observed between the fall group and the non-fall group, reflecting how patients with grade IV KOA transition toward fall risk after compensatory failure. First, regarding hip and knee range of motion, bilateral hip range and right knee range were significantly reduced in the fall group (left hip range: $P < 0.001$; right hip range: $P < 0.001$; right knee range: $P < 0.001$). The magnitude of reduction was substantial: left hip range decreased from a median of 39.8° to 27.95° , and right hip range from 37.5° to 26.6° . This indicates that restricted hip and knee motion during walking in the fall group resulted from a combination of joint pathology, pain, and decreased muscle strength. No significant differences were observed in the minimum angles (flexion) of the hip or knee between the two groups; all differences were concentrated in the maximum angles (extension or peak flexion). This suggests that patients in the fall group were unable to fully extend the hip and knee at the terminal stance phase, thereby compromising forward propulsion efficiency. Gait speed differences confirmed this finding: the fall group had a median gait speed of 0.36 m/s, compared with 0.52 m/s in the non-fall group ($P < 0.001$), representing a typical “slow, cautious, stiff” gait [25]. Regarding plantar pressure and foot progression angle data, contact area was significantly reduced bilaterally in the fall group (left foot: $P = 9 \times 10^{-4}$; right foot: $P = 0.0019$). Simultaneously, step width was abnormally increased in the fall group (left step width: 22.9 vs 10.95; right step width: 22 vs 11.65; both $P < 0.001$). This combination is clinically notable. Although increased step width is generally considered a compensatory strategy for stability, in this context it may represent a form of “pseudo-stability”: patients adopt a widened base of support, but the contact area with the ground is reduced, suggesting they are bearing weight on the medial or lateral borders of the feet rather than through the entire foot. The right foot progression angle was 19.76° in the fall group versus 5.16° in the non-fall group ($P < 0.001$), indicating marked excessive external rotation of the right foot. This is a common clinical compensatory pattern—when hip external rotation is limited, patients may compensate by externally rotating the entire lower limb, which disrupts normal propulsive alignment and increases the risk of lateral falls. The most clinically significant findings were in step length and support phase data. Left step length was 25.9 in the fall group versus 45.75 in the non-fall group; left stride length was 58.3 vs 77.7, with highly significant differences. Although right step length also showed a statistically significant difference (33.5 vs 38.85), the magnitude of difference was smaller on the right side than on the left. This asymmetry is key. Double support time was significantly prolonged in the fall group (left double support: 800 vs 583.35, $P < 0.001$), while single support time was shortened (left single support: 381.65 vs 483.35, $P < 0.001$). Together, these data depict a typical “unstable gait pattern”: patients spend more time with both feet on the ground to maintain stability, but once they enter the single-leg support phase (the most unstable phase of walking), they are unable to maintain support—possibly due to hip abductor weakness or pain-related reluctance to bear weight. Shortened single support time is a valuable fall prediction indicator. Ankle data were less prominent. No significant differences were found between groups in maximum plantarflexion or dorsiflexion angles of either ankle [26]. However, right ankle range of motion was significantly reduced in the fall group (20.15 vs 25.45, $P < 0.001$), and left ankle range also showed a smaller difference ($P = 0.0463$). This may suggest that the ankle strategy is not the primary compensatory mechanism in the fall group, or that ankle pathology is less severe than

hip/knee involvement. Nevertheless, the issues with foot progression angle and step width sufficiently demonstrate disruption of the entire lower limb kinetic chain.

Table 2 Comparison between fall group and non-fall group in patients with grade IV osteoarthritis

Parameter	Fall_Group	No Fall Group	Test	P_value
Left Hip Range	27.95(24.6,31.7)	39.8 (35.4,42.3)	Mann–WhitneyU	<0.001
Left Hip Max	50.6(42.72,54.95)	54.85(51.6,58.6)	Mann–WhitneyU	0.0025
Left Hip Min	21.35 (13.2,25.2)	16.15 (10.3,29.4)	Mann–WhitneyU	0.4634
Right Hip Range	26.6 (20.9,30)	37.5 (34.4,39.2)	Mann–WhitneyU	<0.001
Right Hip Max	47.6 (40.93,53.55)	54.55 (47.8,61.1)	Mann–WhitneyU	0.0011
Right Hip Min	16.75 (8.6,30)	12.9 (6.3,21.7)	Mann–WhitneyU	0.2107
Left Knee Range	40 (29.35,46.8)	44.95 (39.3,53.3)	Mann–WhitneyU	0.1405
Left Knee Max	51.6 (46.12,58.7)	55.25 (48,60.3)	Mann–WhitneyU	0.2105
Left Knee Min	11.9 (9.62,19.75)	11.9 (6.4,17.3)	Mann–WhitneyU	0.8881
Right Knee Range	37.15 (29.35,44.9)	46.25 (40.6,56.7)	Mann–WhitneyU	<0.001
Right Knee Max	49.35 (38.15,54.3)	56.45 (48,71.2)	Mann–WhitneyU	<0.001
Right Knee Min	12.4 (6.9,18.5)	14.6 (10.9,16.7)	Mann–WhitneyU	0.5096
Left Ankle Range	22.2 (19,26.3)	27.4 (20.2,29.9)	Mann–WhitneyU	0.0463
Left Ankle Max	14.85 (10,16.42)	13.4 (11.3,25.4)	Mann–WhitneyU	0.6621
Left Ankle Min	-9.9 (-13.12,-5)	-9.3 (-13.5,-7.6)	Mann–WhitneyU	0.8881
Right Ankle Range	20.15 (17.2,22)	25.45 (22,30.1)	Mann–WhitneyU	<0.001
Right Ankle Max	12.35 (10.2,14.8)	12.35 (10.6,14.8)	Mann–WhitneyU	0.7727
Right Ankle Min	-9.1 (-11.8,-4.7)	-10.8 (-14.3,-7)	Mann–WhitneyU	0.1213
Static Left Anterior	24.5 (18.19,29.99)	26.78 (22.56,27.7)	Mann–WhitneyU	0.1616
Static Left Posterior	28.76 (22.53,33.63)	24.94(23.24,27.58)	Mann–WhitneyU	0.1405
Static Right Anterior	21.31 (20.56,23.88)	20.98 (18.6,24.06)	Mann–WhitneyU	0.2107
Static Right Posterior	25.8 (19.26,32.23)	26.28 (24.74,28.6)	Mann–WhitneyU	0.7167
Dynamic Left Foot	608.3 (533.3,770.8)	557.15(400,716.7)	Mann–WhitneyU	0.1403
Dynamic Right Foot	7633.3 (533.3,783.3)	675 (528.6,716.7)	Mann–WhitneyU	0.8293
Left Foot Impulse	323.6 (268.15,376.1)	349.65(312.5,423.7)	Mann–WhitneyU	0.1048
Right Foot Impulse	290.95 (245.6,340.5)	264.8(188.4,354.4)	Mann–WhitneyU	0.239
Left Foot Contact Area	129.8 (118.12,148.75)	147.35(137.6,166.1)	Mann–WhitneyU	<0.001
Right Foot Contact Area	124.1 (116.78,137.8)	153.8(126.8,160.9)	Mann–WhitneyU	0.0019

(Continued)Table 2 Comparison between fall group and non-fall group in patients with grade IV osteoarthritis				
Left Foot				
Progression	20.37 (11.95,27.02)	16.59 (2.71,24.91)	Mann–WhitneyU	0.1217
Angle				
Right Foot				
Progression	19.76 (14.08,25.72)	5.16 (1.44,9.36)	Mann–WhitneyU	<0.001
Angle				
Left Step Width	22.9 (22,23.5)	10.95 (7.2,18.1)	Mann–WhitneyU	<0.001
Right Step Width	22 (21.8,23.1)	11.65 (7.2,18.9)	Mann–WhitneyU	<0.001
Left Foot Width	11.65 (7.2,13.4)	8.6 (7.9,8.7)	Mann–WhitneyU	0.0076
Right Foot Width	13.29±7.91 (12.2,14.1)	8.65 (6.7,9.5)	Mann–WhitneyU	<0.001
Walking Speed	0.36 (0.26, 0.43)	0.52 (0.43,0.63)	Mann–WhitneyU	<0.001
Left Step Time	766.7 (716.7,920)	766.65 (671.4,833.3)	Mann–WhitneyU	0.1828
Right Step Time	741.65 (733.3,820)	758.35 (750,828.5)	Mann–WhitneyU	0.3746
Left Step Length	25.9 (21.3,34.1)	45.75 (41.1,48)	Mann–WhitneyU	<0.001
Right Step Length	33.5 (28.2,37.12)	38.85 (35.8,47.2)	Mann–WhitneyU	0.0198
Left Stride Length	58.3 (46.5,65.5)	77.7 (68.6,96.8)	Mann–WhitneyU	<0.001
Right Stride Length	56.05 (48.38,66.3)	74.3 (68.6,80.8)	Mann–WhitneyU	<0.001
Left Gait Cycle	150 (1420.85,1572.5)	1525 (1499.9,1666.7)	Mann–WhitneyU	0.303
Right Gait Cycle	1550 (1450,1591.67)	1536.9 (1500,1583.3)	Mann–WhitneyU	0.8586
Left Single Support	381.65 (350,450)	483.35 (428.6,550)	Mann–WhitneyU	<0.001
Right Single Support	400 (295,450)	470 (433.3,483.3)	Mann–WhitneyU	<0.001
Left Double Support	800 (616.7,833.3)	583.3 (533.3,671.4)	Mann–WhitneyU	<0.001
Right Double Support	785 (616.7,883.3)	608.3 (560,633.3)	Mann–WhitneyU	<0.001
Left Total Support	1191.6 (1045.8,1300)	1091.65 (1028.5,1150)	Mann–WhitneyU	0.0117
Right Total Support	1120 (1066.7,1216.7)	1083.35 (1066.7,1183.3)	Mann–WhitneyU	0.2085

3.2 Two-way ANOVA results (main effects and interaction effects of KL grade and fall history)

To investigate the effects of knee osteoarthritis severity (KL grade: III vs. IV) and fall history (yes vs. no) on patients' gait characteristics, a two-way analysis of variance (ANOVA) was

performed to examine the main effects and interaction effects for each gait parameter. The significance level was adjusted using FDR correction, with corrected $p < 0.05$ considered statistically significant. Main effects: KL grade showed significant main effects on several gait parameters, including right foot angle ($F = 7.081$, $p < 0.05$), right step width ($F = 8.516$, $p < 0.05$), left step width ($F=9.863$, $p < 0.05$), right hip max ($F=8.817$, $p<0.05$), right hip range ($F = 6.863$, $p<0.05$), left foot impulse ($F=20.879$, $p<0.001$), static right anterior ($F=8.064$, $p < 0.05$), and left hip max ($F=14.417$, $p<0.05$), indicating that KL grade primarily affects lateral stability, hip joint range of motion, and foot contact characteristics. The main effects of fall history were more extensive, with significant differences observed in almost all temporal, spatial, and pressure-related gait parameters, such as right foot angle ($F=21.067$, $p<0.001$), right step width ($F=318.066$, $p<0.001$), left step width ($F=340.655$, $p<0.001$), and right step time ($F= 13.64$, $p<0.001$), suggesting that fall history leads to more pronounced overall alterations in gait pattern. Interaction effects: Significant interactions between KL grade and fall history were found for the following parameters: right foot angle ($F= 6.339$, $p<0.001$), right step width ($F=14.8$, $p<0.05$), right knee min ($F=10.131$, $p<0.05$), right knee max ($F=10.101$, $p<0.05$), left step width ($F = 9.96$, $p<0.05$), right step time ($F=9.05$, $p<0.05$), and right hip max ($F=7.655$, $p< 0.05$) [27-28]. For some of these parameters (e.g. right knee min, right knee max), the main effects were not significant individually, but their interaction effects were significant, indicating a synergistic modulation between KL grade and fall history: the effect of arthritis severity on gait depends on whether the patient has a fall history, and vice versa. No significant interactions were observed for the remaining parameters (corrected $p > 0.05$). In summary, both KL grade and fall history independently affect gait characteristics in patients with knee osteoarthritis, and significant interaction effects exist for several key gait parameters. These findings suggest that clinical assessment should comprehensively consider both arthritis severity and fall risk to develop personalized rehabilitation interventions, as shown in Table 3.

Table 3 Two-way ANOVA results (main effects and interaction effects of KL grade and fall status)

Gait Parameters	KL grade	KL grade	Fall	Fall history	Interaction	Interaction
	F	p	F	p	F	p
Right Foot Progression Angle	7.081	<0.05	21.067	<0.001	16.339	<0.001
Right Step Width	8.516	<0.05	318.066	<0.001	14.8	<0.05
Right Knee Min	1.276	0.42931 635483871	0.445	0.549322085106383	10.131	<0.05
Right Knee Max	2.784	0.22104 675	4.765	0.051106935483871	10.101	<0.05
Left Step Width	9.863	<0.05	340.655	<0.001	9.96	<0.05
Right Step Time	0.774	0.55579 375	13.64	<0.001	9.05	<0.05
Right Hip Max	8.817	<0.05	7.859	<0.05	7.655	<0.05

Right Ankle Range	0.45	0.64820 49	0.047	0.84596352	6.841	0.06434925
Right Hip Range	6.863	<0.05	8.175	<0.05	5.947	0.0829056
Left Foot Contact Area	2.742	0.22104 675	10.595	<0.05	5.603	0.086747076923076 9
Left Hip Min	5.176	0.07883 325	1.286	0.357137837837838	5.508	0.086747076923076 9
Left Step Length	4.779	0.08747 91666666667	29.53	<0.001	5.381	0.086747076923076 9
Right Knee Range	0.098	0.85598 62666666667	14.119	<0.001	4.653	0.120429214285714
Right Hip Min	4.776	0.08747 91666666667	7	<0.05	4.139	0.150212
Left Foot Impulse	20.879	<0.001	3.321	0.113113219	3.953	0.15665925
Right Single Support	5.352	0.07638 1	12.649	<0.05	3.818	0.159342
Left Foot Width	2.968	0.22104 675	20.178	<0.001	3.373	0.192839052631579
Static Right Posterior	1.487	0.39605 0172413793	1.772	0.263152916666667	3.3	0.192839052631579
Static Right Anterior	8.064	<0.05	0.138	0.740463795918367	3.009	0.209886857142857
Left Hip Max	14.417	<0.05	6.242	<0.05	2.99	0.209886857142857
Left Knee Range	0.156	0.81054 9954545455	11.765	<0.05	2.46	0.276969409090909
Right Step Length	0.031	0.91544 3625	6.945	<0.05	2.29	0.29481547826087
Left Step Time	2.766	0.22104 675	3.103	0.1233795	2.049	0.305105678571429
Left Knee Min	1.092	0.47530 0875	0.644	0.502820860465116	2.043	0.305105678571429
Left Total Support	1.343	0.42302 63	18.017	<0.001	2.035	0.305105678571429
Left Ankle Range	0.737	0.55579 375	0.006	0.938435	1.937	0.305105678571429
Left Ankle Min	2.175	0.28403 8615384615	0.976	0.404566829268293	1.783	0.324291413793103
Right Ankle Max	2.685	0.22104 675	1.136	0.384461538461538	1.485	0.3832225
Right Foot Contact Area	6.12	0.05396 16428571429	9.083	<0.05	0.928	0.523649057142857
Right Stride Length	1.683	0.37069 1678571429	32.725	<0.001	0.908	0.523649057142857
Left Hip Range	11.692	<0.05	8.637	<0.05	0.864	0.523649057142857
Left Foot	0	0.99083	3.073	0.1233795	0.853	0.523649057142857

Progression Angle		2				
Left Double Support	0.336	0.70049 2463414634	17.124	<0.001	0.847	0.523649057142857
Left Ankle Max	0.074	0.85680 9765957447	1.111	0.384461538461538	0.68	0.582867666666667
Dynamic Right Foot	2.155	0.28403 8615384615	6.387	<0.05	0.644	0.584465513513514
Left Knee Max	0.15	0.81054 9954545455	12.895	<0.05	0.564	0.606153307692308
Walking Speed	0.644	0.58431 2513513513	0.73	0.479305285714286	0.541	0.606153307692308
Right Ankle Min	1.044	0.47746 6636363636	0.168	0.72543675	0.479	0.625294425
Right Foot Width	0.072	0.85680 9765957447	36.889	<0.001	0.392	0.650042357142857
Static Left Anterior	0.44	0.64820 49	9.1	<0.05	0.387	0.650042357142857
Static Left Posterior	0.442	0.64820 49	1.034	0.3970605	0.221	0.753234191489362
Left Gait Cycle	0.184	0.81054 9954545455	0.455	0.549322085106383	0.205	0.753234191489362
Right Double Support	0.003	0.97282 194	10.982	<0.05	0.184	0.753234191489362
Right Gait Cycle	0.009	0.96216 912244898	0.499	0.545722666666667	0.157	0.753234191489362
Left Single Support	21.06	<0.001	34.031	<0.001	0.155	0.753234191489362
Right Foot Impulse	19.033	<0.001	2.6	0.159653314285714	0.033	0.91073675
Dynamic Left Foot	3.659	0.15628 5473684211	5.167	<0.05	0.022	0.917009142857143
Left Stride Length	1.635	0.37069 1678571429	33.955	<0.001	0.006	0.95887752
Right Total Support	0.74	0.55579 375	0.523	0.545722666666667	0.001	0.979173

The two-way ANOVA results presented in the table above reveal significant "grade × fall history" interaction effects across multiple key gait dimensions. These interaction effects offer deeper insights than the main effects alone into the gait alterations that increase fall risk. To further compare the differences in key gait parameters between the two patient groups, selected variables including left and right step width, right foot angle, right step time, and right hip/right knee maximum angles were visualized (Fig1–Fig3). Regarding the right foot angle, the interaction plot shows that among patients without a fall history, those with KL grade III maintained a relatively low foot angle. In grade IV patients, however, the foot angle decreased in non-fallers (possibly reflecting compensatory adduction) but increased sharply in fallers. This suggests that patients with severe KOA who have a history of falls exhibit a marked compensatory foot abduction pattern during walking. This may represent a "failed"

lateral stabilization strategy—artificially widening the base of support by increasing the foot angle—but the excessive angle leads to abnormal biomechanical alignment, which in turn increases instability during the mid-to-late stance phase and is directly associated with higher fall risk. The analysis of left and right step width yielded highly consistent results. The interaction plot clearly demonstrates a "grade-dependent fall effect." For patients with KL grade III KOA, fall history had little effect on step width. Among grade IV patients, however, non-fallers exhibited a significantly increased step width, representing a positive and effective compensatory adaptation (widening step width to enhance lateral stability). In contrast, fallers with grade IV KOA failed to increase step width effectively, or even showed a relatively narrower step width. This reveals a critical issue: as KOA progresses to grade IV, the body should compensate by widening step width, but individuals with a fall history may lose this effective compensatory ability due to impaired neuromuscular control, muscle weakness, or pain, leading to a pronounced deficit in basic gait stability. The box plots further corroborate the abnormal distribution of step width in the grade IV faller group. These findings indicate that foot angle and step width are sensitive indicators for identifying KOA patients at high risk of falls. Among grade IV KOA patients, those exhibiting "failed foot angle compensation" and "failure to widen step width" have a significantly elevated fall risk. The interaction plot for right step time revealed a crossover effect. Among grade III KOA patients, individuals with a fall history actually had shorter step times (faster step frequency). This may reflect an "overly vigilant or fear-driven hurried gait," attempting to pass through unstable periods quickly, but potentially at the cost of reduced motor control precision. In grade IV KOA patients, the pattern reversed: those with a fall history showed significantly prolonged step time, consistent with a more typical "cautious, slow, protective gait." This transition from a "hurried" pattern in grade III to a "slow" pattern in grade IV, along with the significant interaction, strongly suggests that disease severity fundamentally alters the neural strategies of gait adaptation following a fall. When grade IV patients have a fall history, their gait rhythm becomes abnormally slow and hesitant, which is itself a marker of dual declines in mobility and confidence. The interaction plot for right hip maximum extension angle showed that among patients without a fall history, progression from KL grade III to IV was associated with a significant increase in hip extension angle, possibly representing an attempt to compensate by lengthening the step. However, among patients with a fall history, hip extension angles remained at a relatively low and similar level regardless of whether KL grade was III or IV. This suggests that a fall history "suppresses" the compensatory potential of the hip joint. Individuals with a fall history already exhibit limited hip extension even in early-stage KOA (grade III), which restricts effective step lengthening and represents an important mechanism affecting walking efficiency and obstacle-crossing ability. The interaction plot for right knee maximum flexion angle revealed two interesting trends. First, in the non-faller group, knee flexion angle decreased slightly from grade III to IV, consistent with the expected reduction in range of motion as the disease progresses. Second, among grade III patients, those with a fall history had a slightly higher knee flexion angle than non-fallers. This may represent an early compensatory strategy, attempting to cushion impact or alter loading patterns by increasing knee flexion. However, this difference disappeared at grade IV, indicating that any compensatory joint movement adjustments present in the early stage become ineffective as

KOA enters the advanced stage, with generalised joint function limitation becoming dominant.

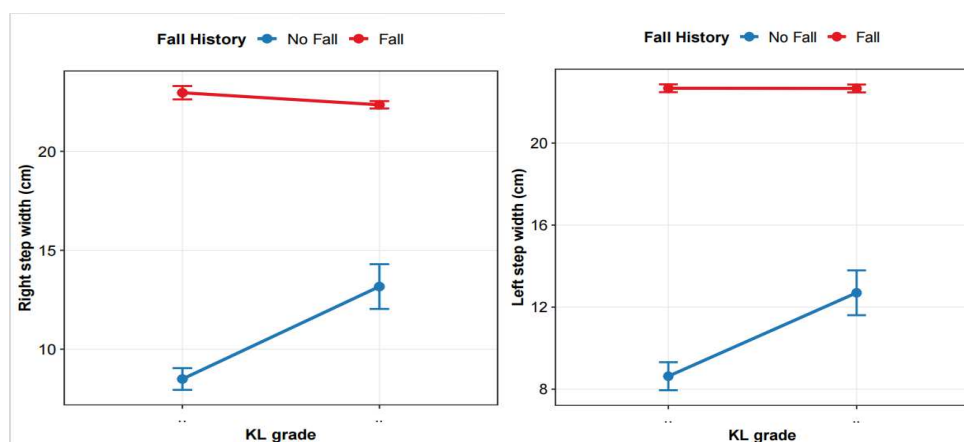


Figure 1. Interaction plot of right step width and left step width

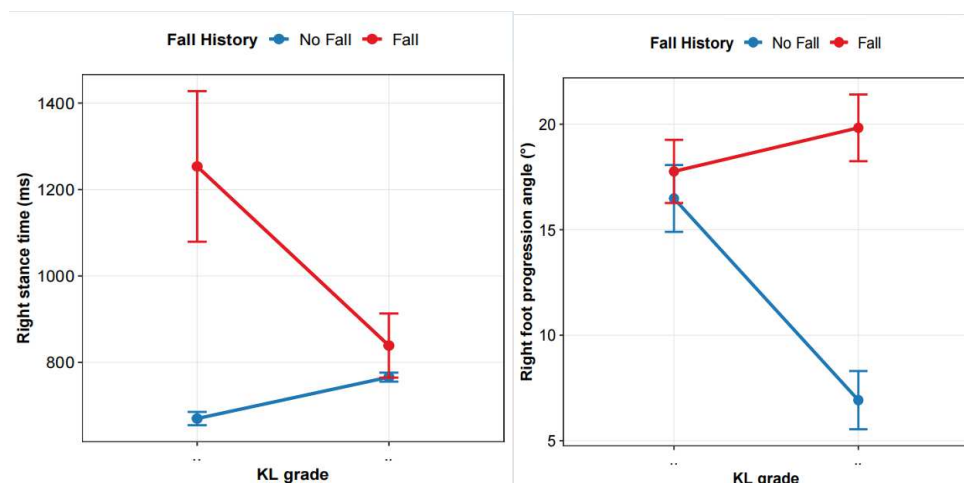


Figure 2. Interaction plot of right foot step duration and right foot progression angle

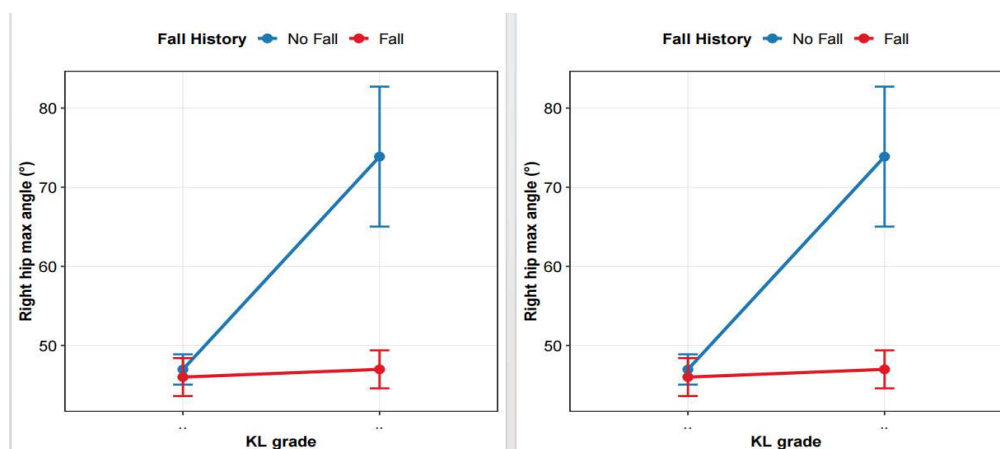


Figure 3. Interaction plot of right hip max and right knee max

3.3 Screening of fall risk predictors

To further analyze factors associated with falls in patients with osteoarthritis, univariate logistic regression analyses were performed on candidate variables. To preliminarily assess the relationship between each gait parameter and fall risk, 20 selected gait parameters were each subjected to univariate logistic regression analysis. The results are shown in Table 4. Among these, 14 variables—including left total stance, right single support, left step width, right step width, right hip max, right hip range, left hip range, right knee max, right knee range, left knee range, left foot contact area, right foot contact area, right step length, and left step length—were significantly associated with fall risk ($P < 0.05$). Gait speed did not reach statistical significance in the univariate analysis ($OR = 0.714$, $P = 0.447$), but due to its clinical importance, it was still included in the subsequent Lasso screening. "Right total stance" was excluded from further analysis because its odds ratio was close to 1 and $P > 0.05$. At the selected λ value, Lasso regression compressed the coefficients of most variables to zero, ultimately identifying eight variables with non-zero coefficients. Their coefficients and directions are presented in Table 4.

Table 4. Univariate logistic regression analysis of gait parameters in patients with osteoarthritis.

Variable	OR	Lower_CI	Upper_CI	P
Left total support	1.00 4	1.00 2	1.006	<0.001
Right single support	0.99 1	0.98 5	0.996	<0.001
Right total support	1	1	1.001	0.495
Left foot impulse	0.99 7	0.99 3	1.001	0.101
Right foot impulse	1.00 3	0.99 9	1.007	0.135
Left gait cycle	1	0.99 9	1	0.526
Right gait cycle	1	0.99 9	1	0.505
Left step width	2.63 5	1.78 5	4.752	<0.001
Right step width	2.00 2	1.53 5	3.078	<0.001
Right hip max	0.97 3	0.94 4	0.993	<0.001
Right hip range	0.93 8	0.88 8	0.982	<0.001
Left hip range	0.9 48	0.90 8	0.983	<0.001

Right knee max	0.9 69	0.93 9	0.998	<0.001
Right knee range	0.9 47	0.91 5	0.976	<0.001
Left knee range	0.9 55	0.92 6	0.982	<0.001
Left foot contact area	0.9 69	0.94 8	0.988	<0.001
Right foot contact area	0.9 81	0.96 7	0.994	<0.001
Right step length	0.9 61	0.92 9	0.989	<0.001
Left step length	0.9 19	0.88 2	0.952	<0.001
Gait speed	0.7 14	0.19	1.408	0.447

To avoid multicollinearity and select the core variables with the greatest predictive value, Lasso regression with 10-fold cross-validation was further employed for variable selection. Fall history (faller=1, non-faller=0) was used as the dependent variable, and all 20 gait parameters were entered into the Lasso model. Based on the cross-validation error curve, the λ value under the "one-standard-error rule" was selected as the optimal penalty parameter, i.e., $\lambda_{1se} = 0.000298$ (Fig 4).

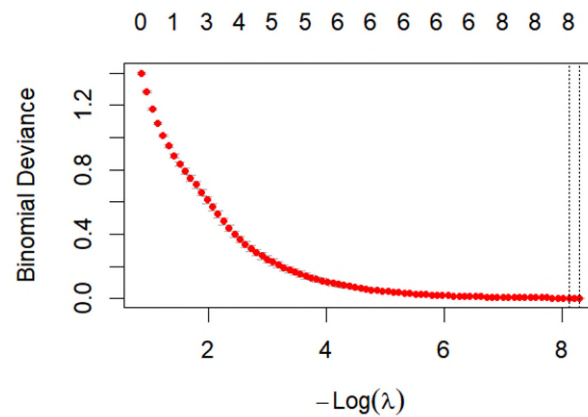


Figure 4 Cross-validation curve for Lasso regression with the one

Under this λ value, Lasso regression compressed the coefficients of most variables to zero, ultimately identifying eight variables with non-zero coefficients. Their coefficients and directions are presented in Table 5.

table 5 Variables with non-zero coefficients retained by Lasso regression

Variable	Coefficient
Left step width	0.517349177740082
Right step width	0.937301158156702
Right hip max	-0.050738214
Left hip range	0.00680653596246759
Right knee max	-0.063614274
Right knee range	-0.030615426
Left step length	-0.146889077
Gait speed	0.0661411372237888

Note: The positive coefficient for gait speed may be related to multicollinearity or sample characteristics. This discrepancy likely arises from strong collinearity between gait speed and step width/step length, leading to a sign reversal during the coefficient shrinkage process of Lasso regression. Given that gait speed was not statistically significant in the multivariate model and its clinical significance is partially accounted for by step width and step length, it was not included as an independent predictor in the final model.

3.4 Multivariate Firth regression and final prediction model

Based on the univariate logistic regression and Lasso regression analyses, candidate variables were further analyzed, and collinearity among independent variables was examined. Strong correlations were detected among some variables during collinearity diagnostics. Therefore, variables were selected by combining statistical results with clinical significance, and the final multivariate logistic regression model included average step width, right hip max, left hip range, right knee max, right knee range, left step length, and gait speed. Since left and right step width selected by Lasso exhibited extreme multicollinearity ($VIF > 80$), they were replaced by average step width. When fitting a standard logistic regression model, complete separation was observed for average step width between the faller and non-faller groups (no overlap in step width between the two groups), leading to failure of maximum likelihood estimation. Consequently, Firth penalized likelihood logistic regression was employed for multivariate analysis, as this method can handle complete separation and provide stable parameter estimates. Seven variables—average step width, right hip max, left hip range, right knee max, right knee range, left step length, and gait speed—were entered into the Firth regression model. The results are shown in Table 6. After adjustment, average step width was identified as an independent risk factor for falls (OR = 1.958, 95% CI: 1.528–10.491, $P < 0.001$) [29], indicating that each 1 cm increase in average step width was associated with an approximately 96% increase in fall risk. Left step length was a protective factor (OR = 0.932, 95% CI: 0.821–0.983, $P = 0.007$): each 1 cm increase in left step length reduced fall risk by approximately 7%. The remaining variables (right hip max, left hip range, right knee max, right knee range, and gait speed) were not statistically significant ($P > 0.05$). Among them, gait speed showed an OR of 0.837 ($P = 0.625$) in the multivariate model, suggesting that after controlling for step width and step length, gait speed was no longer an independent predictor, and its positive coefficient

in Lasso likely resulted from collinearity with step width and step length. Due to the presence of complete separation, a conventional ROC curve could not be accurately estimated; nevertheless, the Firth regression results remain reliable. Based on these results, a nomogram for predicting fall risk was constructed[30], allowing clinicians to input a patient's average step width and left step length to quickly estimate individualized fall probability. The color gradient in the figure represents the predicted fall risk (blue for low risk, red for high risk), showing that fall risk increases markedly when average step width widens and left step length shortens.

Table 6. Firth regression analysis in patients with osteoarthritis.

Variable	OR	95% CI	P 值
Mean step width	1.958	1.528–10.491	<0.001
Right hip max	0.982	0.839–1.056	0.4849
Left hip range	0.990	0.831–1.465	0.7249
Right knee max	1.008	0.358–1.410	0.9626
Right knee range	0.964	0.537–2.631	0.8119
Left step length	0.932	0.821–0.983	0.0065
Gait speed	0.837	0.039–2.420	0.6249

Note: The upper bound of the 95% confidence interval for average step width is large (10.49). This is because complete separation between the two groups resulted in a wide confidence interval, though the point estimate of the OR remains robust. Average step width showed no overlap between fallers and non-fallers (22–23 cm vs. 8–10 cm, respectively), which is a classic case of “complete separation”. Although the Firth penalized likelihood regression yielded a convergent point estimate (OR=1.958), the standard error was relatively large, leading to a wide confidence interval (upper bound reaching 10.49). This does not negate the practical predictive value of step width, but rather indicates some uncertainty regarding the effect size in the current sample. External validation or expansion of the sample size is warranted to obtain a more precise estimate.

Based on the two significant variables identified in the Firth regression (average step width and left step length), a heatmap for fall risk prediction was generated. The heatmap visually demonstrates that when average step width exceeds 18 cm and left step length is less than 35 cm, the predicted fall probability exceeds 0.75 (red region). Conversely, when step width is less than 12 cm and step length exceeds 45 cm, the risk is below 0.25 (blue region). This heatmap can serve as a rapid clinical screening tool, allowing clinicians to directly determine the risk level based on a patient's step width and step length. (Fig 5)

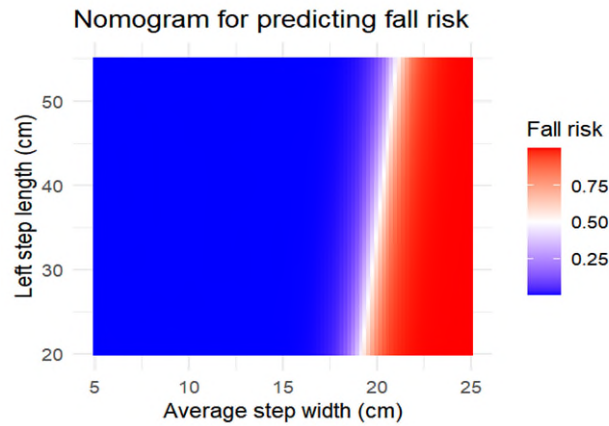


Figure 5 Heatmap of predicted fall probability based on mean step width and left step length

Note: The horizontal axis represents average step width (cm), and the vertical axis represents left step length (cm). The color gradient indicates the predicted probability of falling (blue: low risk, red: high risk). As average step width increases and left step length decreases, fall risk rises markedly. The red region in the figure is mainly concentrated in the area where step width > 18 cm and step length < 35 cm, indicating that patients in this region are at high risk of falls. Of note, due to complete separation of average step width between the two groups, the upper bound of its confidence interval is wide (10.49), but the direction of the effect is clear.

3.5 Model stability validation and final prediction model

Based on the sole independent predictor identified by multivariate Firth regression—average step width—a univariate Firth logistic regression model was constructed. The model fitting results showed that each 1 cm increase in average step width was associated with an approximately 1.24-fold increase in fall risk (OR = 2.24, 95% CI: 1.58–3.91, $P < 0.001$). Bootstrap internal validation (1,000 resamples with replacement) was performed to assess model stability. The results demonstrated 100% sign consistency for the regression coefficient of average step width, with a median bootstrap AUC of 0.960 (95%CI: 0.920–0.992), as shown in Table 7. Leave-one-out cross-validation (LOOCV) yielded an AUC of 0.956 (95% CI: 0.911–0.991), an overall accuracy of 95.8%, a sensitivity of 100%, and a specificity of 91.7%, with no apparent overfitting (Fig 6). Decision curve analysis (DCA) showed that within the threshold probability range of 0.2–0.7, the net benefit of the step-width-based prediction model was significantly higher than that of the “intervene for all” or “intervene for none” strategies. For example, at a threshold probability of 0.2, the net benefit was approximately 0.32, meaning that an additional 32 patients who would truly experience a fall could be correctly identified per 100 patients (Fig 7). These findings fully demonstrate that the model has good clinical utility and can assist clinicians in making more accurate individualised fall prevention decisions.

Table 7. Summary of univariate Firth logistic regression model performance

Indicator	Value
-----------	-------

Indicator	Value
Odds ratio (95% CI)	2.24 (1.58–3.91)
LOOCV AUC (95% CI)	0.956 (0.911–0.991)
LOOCV accuracy	0.958
LOOCV sensitivity	1.000
LOOCV specificity	0.917
Bootstrap AUC median (95% CI)	0.960 (0.920–0.992)
Coefficient sign consistency for mean step width	100%

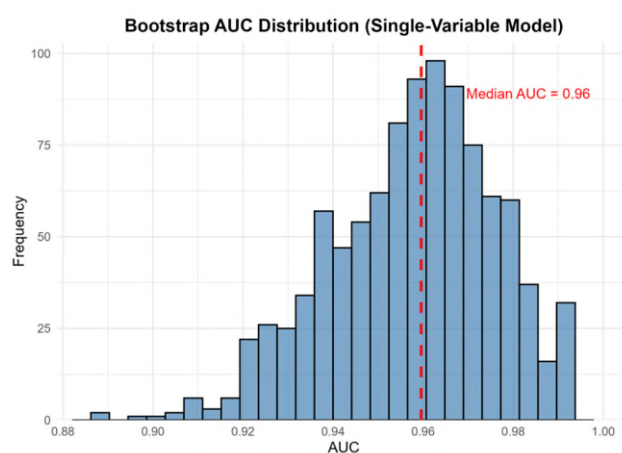


Figure 6 Receiver operating characteristic (ROC) curve of the univariate step-width prediction model assessed by leave-one-out cross-validation (LOOCV).

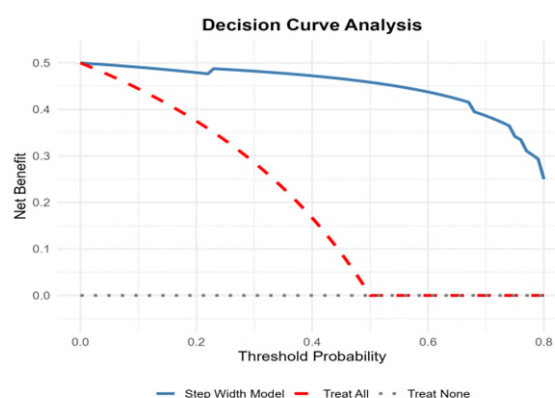


Figure 7 Decision curve analysis (DCA) for the clinical net benefit of the step-width prediction model.

4. Conclusion

4.1 Gait characteristics and fall risk in patients with moderate-to-severe KOA

This study systematically analyzed the gait biomechanical characteristics of patients with moderate-to-severe (Kellgren–Lawrence grades III–IV) knee osteoarthritis (KOA) and their relationship with fall risk. The results showed that patients with a fall history exhibited a typical high-risk gait pattern: reduced gait speed, shortened step length, prolonged double support phase, limited joint range of motion, and significantly widened step width. These findings are consistent with previous studies showing that KOA patients adopt a cautious, protective gait strategy to enhance walking stability, but this strategy simultaneously compromises gait flexibility and may paradoxically increase fall risk [31–32].

4.2 Interaction effects between KL grade and fall history

The interaction effects revealed by two-way ANOVA provide critical clinical insights. Among patients with KL grade IV, those with a fall history showed a marked increase in foot angle and a weakened tendency to widen step width compared to non-fallers. This suggests that as arthritis progresses to grade IV, the compensatory capacity for maintaining lateral stability may be partially lost due to impaired neuromuscular control. The fall event itself may accelerate the deterioration of gait strategies, creating a vicious cycle—a finding consistent with an exploratory study on fall prediction following balance perturbations in KOA patients published in BMC Musculoskeletal Disorders[33] .

4.3 Biomechanical basis of step width as a core predictor

Average step width remained highly stable across multivariate analysis, LOOCV, and bootstrap validation, and was the only predictor achieving 100% sign consistency. From a biomechanical perspective, step width directly reflects lateral stability during walking—widening the step width reduces the mediolateral excursion of the center of mass in the frontal plane and represents a common conservative gait strategy [34]. The complete non-overlap in step width between fallers and non-fallers in this study further supports the value of step width as a risk stratification tool for falls in KOA patients. Our contribution lies in quantifying the predictive value of step width for the first time in patients with moderate-to-severe KOA and validating its robustness. Notably, although other parameters such as step length were initially significant in multivariate analysis, bootstrap validation showed a sign consistency of only 32.8%, suggesting that these effects may be substantially influenced by sample variability.

4.4 Clinical implications and practical value

The univariate step-width prediction model constructed in this study has good clinical utility. Decision curve analysis showed that within a threshold probability range of 0.2–0.7, the net benefit of using the step-width model to guide interventions was consistently superior to the “intervene for all” or “intervene for none” strategies. This means that clinicians can confidently use the model to make individualized decisions while avoiding overtreatment or missed diagnoses. Based on the study findings, we propose the following clinical operational recommendations: when a patient’s average step width is <12 cm, fall risk is very low (normal walking); when step width is 12–18 cm, comprehensive assessment combined with other factors is needed; when step width is >18 cm, the

patient should be considered at high risk of falls [35], and immediate fall prevention interventions are recommended (including gait training, use of walking aids, balance training, and home environment modification). Step width measurement requires no expensive equipment; clinicians can quickly assess it using a soft tape measure or even observation during routine outpatient visits, providing an economical and practical tool for primary healthcare facilities and community screening.

4.5 Limitations and future directions

This study has several limitations: (1) the sample was derived from a single center, which may introduce selection bias[36] ; (2) complete separation of step width between the two groups leads to extreme predicted probabilities, making step width more suitable as a risk stratification tool than for absolute probability estimation; (3) fall history was retrospectively collected, which may introduce recall bias; (4) gait variability indices and muscle activation patterns were not included. Future multicenter prospective cohort studies are needed to validate the findings, and combined prediction models integrating step width with other clinical variables should be explored.

5 Declarations

5.1 Ethics approval and consent to participate

This study was approved by the Ethics Committee of the Second Hospital of Shanxi Medical University (approval number: (2026) YX No. 207). Written informed consent was obtained from all participants. All procedures were performed in accordance with the relevant guidelines and regulations.

5.2 Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

5.3 Competing interests

The authors declare that they have no competing interests.

5.4 Funding

This research was funded by the Key Research and Development Project of Shanxi Province, grant number 202202150401019 (project title: "Intelligent Research and Application of Gait Analysis Based on Big Data Platform in Sports System Injury Diseases"; principal investigator: Pengcui Li).

5.5 Authors' contributions

YW, NDR, and DP contributed to study design, data collection, and analysis. PL supervised the study and revised the manuscript. All authors read and approved the final manuscript.

5.6 Acknowledgements

None.

5.7 Clinical trial number

Not applicable.

References

- [1] He K, Sun GJ, Yin Y, et al. Risk factors and a risk forecasting model for falls in aged patients with knee osteoarthritis. *J Tradit Chin Orthop Traumatol*, 2024, 36(03): 23-30.
- [2] Galea MP, Levinger P, Lythgo N, et al. A targeted home- and center-based exercise program for people after total hip replacement: a randomized clinical trial. *Arch Phys Med Rehabil*, 2013, 94(7): 1247-1253.
- [3] Levinger P, Menz HB, Morrow AD, et al. Lower limb biomechanics in individuals with knee osteoarthritis before and after total knee arthroplasty surgery. *J Arthroplasty*, 2013, 28(6): 994-999.
- [4] Ewen AM, Gribble PA, Hertel J. Kinematic predictors of falls in community-dwelling older adults: a systematic review. *J Geriatr Phys Ther*, 2019, 42(3): 175-188.

-
- [5] Organization W H.WHO global report on falls prevention in older age[J].Who Global Report on Falls Prevention in Older Age,2007.
 - [6] Auais M,Alvarado B,Guerra R, et al.Fear of falling and its association with life-space mobility of older adults: a cross-sectional analysis using data from five international sites[J].Age & Ageing,2017,46(3):459-465.
 - [7] Kim D,Geert C,Guy V, et al.Fear-related avoidance of activities, falls and physical frailty. A prospective community-based cohort study[J].Age & Ageing,2004,33(4):368-373.
 - [8] Li F,Fisher K J,Harmer P, et al.Fear of falling in elderly persons: association with falls, functional ability, and quality of life[J].J Gerontol B Psychol Sci Soc Sci,2003,58(5):283-290.
 - [9] Maki BE, McIlroy WE. Control of rapid limb movements for balance recovery: age-related changes and implications for fall prevention. Age Ageing, 2006, 35(suppl 2): ii12-ii18.
 - [10] Alghadir A, Anwer S, Iqbal A, et al. Test-retest reliability and validity of the Footscan® platform system in healthy subjects. Journal of Physical Therapy Science, 2015, 27(12): 3815-3818.
 - [11] Buldt AK, Allan JJ, Landorf KB, Menz HB. The reliability of the Footscan® platform system for measuring plantar pressure in older people. Journal of Foot and Ankle Research, 2014, 7(Suppl 1): A46.
 - [12] Heinze G, Schemper M. A solution to the problem of separation in logistic regression. Stat Med, 2002, 21(16): 2409-2419.
 - [13] Puhr R, Heinze G, Nold M, et al. Firth's logistic regression with rare events. J Clin Epidemiol, 2017, 86: 86-94.
 - [14] Tibshirani R. Regression shrinkage and selection via the lasso. J R Stat Soc B, 1996, 58(1): 267-288.
 - [15] Steyerberg EW. Clinical Prediction Models. Springer, 2009.
 - [16] Hastie T, Tibshirani R, Friedman J. The Elements of Statistical Learning. Springer, 2009.
 - [17] Fitzgerald M, Saville BR, Lewis RJ. Decision curve analysis. JAMA, 2015, 313(4): 409-410.
 - [18] Faul F, Erdfelder E, Lang AG, Buchner A. G*Power 3. Behav Res Methods, 2007, 39(2): 175-191.
 - [19] Hausdorff JM, Rios DA, Edelberg HK. Gait variability and fall risk. Arch Phys Med Rehabil, 2001, 82(8): 1050-1056.
 - [20] Maki BE, McIlroy WE. Control of rapid limb movements for balance recovery. Age Ageing, 2006, 35(suppl 2): ii12-ii18.
 - [21] van der Esch M, Steultjens M, Knol DL, et al. Joint proprioception and function in knee OA. Arthritis Care Res, 2007, 57(5): 787-793.
 - [22] Levinger P, Nagle S, Wee E, et al. Gait patterns and falls in knee OA. J Geriatr Phys Ther, 2012, 35(3): 129-135.

-
- [23] Kim D, Geert C, Guy V, et al. Fear-related avoidance of activities, falls and physical frailty. *Age Ageing*, 2004, 33(4): 368-373.
- [24] Hof AL, Gazendam MG, Sinke WE. The condition for dynamic stability. *J Biomech*, 2005, 38(1): 1-8.
- [25] Hiyama Y, Wada O, Yamada M. Knee OA severity and gait characteristics. *J Orthop Sci*, 2017, 22(5): 892-897.
- [26] Williams DS 3rd, Murray AM, LeBlanc M. Gait characteristics and fall risk in older adults with knee OA. *J Geriatr Phys Ther*, 2020, 43(4): 215-225.
- [27] van der Esch M, Knoop J, van der Leeden M, et al. Clinical osteoarthritis of the hip and knee and fall risk. *Rheumatology*, 2020, 59(10): 2910-2919.
- [28] Knoop J, Steultjens MP, van der Leeden M, et al. Proprioception in knee osteoarthritis: a narrative review. *Osteoarthritis Cartilage*, 2011, 19(4): 381-388.
- [29] Xu SC, Li YW, Zhang YQ, et al. Predictive value of 3D kinematic and kinetic parameters for fall risk in elderly KOA patients. *J Zhengzhou Univ (Med Sci)*, 2025, 60(6).
- [30] Iasonos A, Schrag D, Raj GV, Panageas KS. How to build and interpret a nomogram for cancer prognosis. *J Clin Oncol*, 2008, 26(8): 1364-1370.
- [31] Alghadir A, Anwer S, Iqbal A, et al. Test-retest reliability and validity of the Footscan® platform system in healthy subjects. *J Phys Ther Sci*, 2015, 27(12): 3815-3818.
- [32] Xu SC, Li YW, Zhang YQ, et al. Predictive value of three-dimensional kinematic and kinetic parameters of the affected limb for fall risk in elderly patients with knee osteoarthritis. *J Zhengzhou Univ (Med Sci)*, 2025, 60(6): xxx-xxx.
- [33] Branco F, Alves G, Seabra D, et al. Knee osteoarthritis and risk of falls: a systematic review. *BMC Musculoskelet Disord*, 2021, 22(1): 514.
- [34] Paterson KL, Hinman RS, Metcalf BR, et al. Gait characteristics and falls in people with knee OA. *Arthritis Care Res*, 2016, 68(5): 656-664.
- [35] 中华医学会骨科学分会. 骨关节炎诊疗指南(2018 年版). *中华骨科杂志*, 2018, 38(12): 705-715.
- [36] Lord SR, Sherrington C, Menz HB. *Falls in Older People: Risk Factors and Strategies for Prevention*. Cambridge, 2007.
