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Association Between Average Step Width and History of Falls in Patients with Moderate-to-Severe Knee Osteoarthritis: A Cross-Sectional Gait Analysis

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Abstract

Purpose: To investigate the association between average step width and a history of falls in patients with moderate-to-severe knee osteoarthritis (KOA), and to determine whether this association is independent of Kellgren-Lawrence (KL) grade and other potential confounders.Methods: A cross-sectional study was conducted. A total of 120 patients with KL grade III–IV KOA were recruited from the orthopaedic outpatient and inpatient departments of a tertiary hospital between June and December 2026, including 60 patients with a history of falls in the past year and 60 without. Spatiotemporal, kinetic, and kinematic parameters were collected using the Footscan® plantar pressure gait analysis system. The primary exposure was average step width, and the primary outcome was a history of falls within the past year. Two-way ANOVA was used to examine the main and interaction effects of KL grade and fall history on gait parameters. Firth's penalized-likelihood logistic regression was used to evaluate the independent association between average step width and fall history, adjusting for age, sex, BMI, KL grade, and walker use. Internal validation was performed using bootstrap and leave-one-out cross-validation (LOOCV), and decision curve

analysis (DCA) was used to assess exploratory clinical net benefit.Results: Average step width was significantly larger in the fall history group than in the no-fall group (approximately 22.9 cm vs. 8.8 cm, $P < 0.001$), accompanied by slower gait speed, shorter step length, and prolonged double support time. Two-way ANOVA revealed significant interaction effects between KL grade and fall history for several gait parameters ($P < 0.05$). After adjusting for confounders, average step width remained independently associated with a history of falls (OR = 2.97, 95% CI: 1.71–8.49, $P < 0.001$). Internal validation showed high discrimination, with an LOOCV AUC of 0.956, a median bootstrap AUC of 0.960, a sensitivity of 100%, and a specificity of 91.7%; however, due to quasi-complete separation of step width between groups, these performance metrics may be overestimated. DCA suggested a certain net benefit, but this was an exploratory analysis within the same cohort.Conclusions: In patients with moderate-to-severe KOA, average step width is independently associated with a history of falls and may serve as a low-cost, easily accessible candidate associative indicator. Given the cross-sectional design, retrospective collection of fall history, and quasi-complete separation of step width, it cannot be inferred that average step width predicts future falls or has a causal relationship. The reference threshold of approximately 18 cm in this sample should only be considered for clinical risk stratification after multicentre, prospective external validation.

Keywords: Knee osteoarthritis; Step width; Falls; Gait analysis; Cross-sectional study

1 Introduction

Knee osteoarthritis (KOA) is a degenerative joint disease that is highly prevalent among middle-aged and older adults and often leads to chronic pain, restricted joint mobility, and gait abnormalities. Previous studies have shown that the incidence of falls in patients with KOA is 2–3 times higher than in healthy peers, and approximately 40–60% of patients with KOA experience at least one fall annually [1]. Falls can lead to fractures, soft tissue injuries, reduced mobility, and even increased mortality risk[2]; therefore, identifying fall-related factors is of great importance. Typical gait abnormalities in patients with KOA include reduced gait speed, shortened step length, prolonged stance phase, and restricted joint range of motion[3]. Current studies have largely focused on these alterations, which do reflect an overall decline in walking function in patients with KOA. However, step width, as a direct spatiotemporal indicator of frontal plane dynamic stability, remains relatively understudied in patients with moderate-to-severe KOA [4].Step width reflects the lateral distance between the two feet during walking and is an important strategy for maintaining lateral balance and enlarging

the base of support. Biomechanical studies suggest that when balance control declines or fear of falling is present, individuals often increase step width to improve stability; however, excessive widening of step width may also indicate compensatory failure, decreased neuromuscular control, or abnormal biomechanical alignment, thereby being associated with an increased risk of falls. In patients with moderate-to-severe KOA, step width alterations may be particularly pronounced because of more severe joint structural damage, greater pain, and more prominent declines in muscle strength and proprioception. However, systematic analyses of the relationship between average step width and a history of falls in patients with Kellgren-Lawrence grade III–IV KOA are still lacking. Moreover, previous studies have often not adequately adjusted for potential confounders such as KL grade and walker use.Step width measurement is simple, inexpensive, and reproducible, with good clinical accessibility; therefore, it is necessary to examine it as a pre-specified primary variable. Accordingly, this study used a cross-sectional gait analysis design to compare average step width between patients with moderate-to-severe KOA with and without a history of falls and to examine whether average step width remains independently associated with a history of falls after adjusting for age, sex, BMI, KL grade, and walker use. We hypothesized that patients with moderate-to-severe KOA and a history of falls would have a larger average step width than those without a history of falls, and that this association would be independent of arthritis severity and other confounders. It should be emphasized that this study does not evaluate the ability of step width to predict future falls; the results are intended only to generate hypotheses and to provide a basis for subsequent multicentre, prospective cohort validation.

2 Methods

2.1Study participants

A convenience sampling method was used to recruit patients with KOA from the orthopaedic outpatient and inpatient departments of a tertiary hospital between June and December 2026. A total of 120 patients were included, comprising 60 patients with a history of falls within the past year and 60 without such a history.Inclusion criteria were: (1)meeting the American College of Rheumatology diagnostic criteria for KOA;(2)Kellgren-Lawrence(K-L)gradeIII–IV (moderate-to-severe); (3) age 50–85 years; (4) ability to walk independently for more than 10 m (walker use permitted); and (5) informed consent and voluntary participation. Exclusion criteria were: (1) other types of arthritis (e.g rheumatoid arthritis, gouty arthritis); (2) previous knee replacement surgery; (3) severe neurological diseases affecting walking function (e.g Parkinson's disease, sequelae of stroke); (4) severe cardiopulmonary disease preventing completion

of gait testing; (5) cognitive impairment preventing cooperation with testing; and (6) acute lower limb injury or acute exacerbation of pain. According to whether they had a history of falls within the past year, participants were divided into a fall group and a non-fall group. A fall was defined as "an unexpected, involuntary, unintentional change in body position that results in coming to rest on the ground or a lower surface" [5-8].

2.2 Collection of general data

A standardized questionnaire was used to collect the following data: (1) demographic characteristics: age, sex, height, weight, and body mass index (BMI) = weight (kg) / height² (m^2); (2) clinical characteristics: K-L grade (III/IV) and disease duration; and (3) fall-related factors: history of falls within the past year (yes/no), number of falls, walker use, chronic diseases (hypertension/diabetes/stroke), medication use (whether related drugs were used), visual status, cognitive impairment, fear of falling, and environmental factors.

2.3 Gait parameter acquisition

A Footscan® plantar pressure gait analysis system (RSscan International, Belgium) was used to collect gait parameters[9]. The system consisted of a 2-m pressure platform (sampling frequency 500 Hz), a data acquisition unit, and analysis software. The system has been demonstrated to have good reliability and validity [10-11].The testing procedure was as follows: (1) before testing, the procedure was explained to participants, and adaptive walking practice was performed; (2) participants walked barefoot on the pressure platform at their natural gait speed, and a trial was considered valid when each foot fully contacted the platform; (3) three valid trials were collected for each participant, and the average was used for analysis; and (4) during testing, a trained professional stood nearby to protect against falls. All tests were conducted under uniform lighting on a flat surface, with ambient noise controlled below 40 dB.

The gait parameters collected included: spatiotemporal parameters: gait speed (m/s), left/right step length (cm), left/right stride length (cm), left/right step width (cm), left/right step time (ms), left/right gait cycle time (ms), left/right single support time (ms), left/right double support time (ms), and left/right total support time (ms). Kinetic parameters: static left/right forefoot/hindfoot weight-bearing ratio (%), dynamic left/right foot force ratio, left/right impulse, left/right contact area (cm^2), and left/right foot progression angle (°). Kinematic parameters: left/right hip range of motion (°), hip maximum/minimum (°), left/right knee range of motion (°), knee maximum/minimum (°), left/right ankle range of motion (°), and ankle maximum/minimum (°).

2.4 Quality control

(1) Data collection was performed by two uniformly trained researchers to ensure standardized operation; (2) the calibration status of the equipment was checked before gait testing to ensure data accuracy; (3) data entry was independently performed and verified by two researchers; and (4) outliers were rechecked against original records and excluded if necessary.

2.5 Statistical analysis

All statistical analyses were performed using R software (version 4.6.0; R Foundation for Statistical Computing, Vienna, Austria). For quantitative data, normality was first assessed using the Shapiro-Wilk test. Normally distributed data were described as mean ± standard deviation (SD), and comparisons between two groups were performed using independent-sample t-tests (Levene's test for homogeneity of variance). Non-normally distributed data were described as median (interquartile range, IQR), and between-group comparisons were performed using the Mann-Whitney U test. Categorical data were expressed as frequency (percentage), and between-group comparisons were performed using the chi-square test or Fisher's exact test [12-13].To assess the main and interaction effects of KOA severity (K-L grade: III vs IV) and fall history (yes vs no) on gait parameters, two-way ANOVA was used, with significance levels adjusted by FDR correction; a corrected $P< 0.05$ was considered statistically significant.To avoid overfitting due to data-driven selection, the primary association analysis strictly used pre-specified variables. With a history of falls within the past year (1 = yes, 0 = no) as the dependent variable and average step width (the primary exposure variable) as the independent variable, five clinical confounders were adjusted for: age, sex, BMI, KL grade, and walker use. Because fear of falling has an obvious reverse causal relationship with fall history (falling leads to fear), it was excluded from the adjusted model. Because average step width showed quasi-complete separation between the two groups (fall group step width concentrated at 20.65–25.10 cm, no-fall group concentrated at 3.35–22.75 cm, with minimal overlap), maximum likelihood estimation in ordinary logistic regression failed; therefore, Firth's penalized-likelihood logistic regression was used for multivariable analysis to estimate the independent association of each variable with a history of falls and to calculate odds ratios (ORs) and 95% confidence intervals (CIs). Multicollinearity was diagnosed using the variance inflation factor (VIF).In addition, to preliminarily explore the association of other gait parameters with fall history and to assess stability, exploratory analyses were performed: univariate Firth regression was used for preliminary screening of candidate variables, and LASSO regression with 10-fold

cross-validation combined with bootstrap (1,000 resamples) [14] was further used to calculate the selection frequency of each variable. These results were presented only as supplementary material and were not used for the construction of the primary model.Model stability was assessed using bootstrap internal validation (1,000 resamples) to calculate the optimism-corrected AUC, calibration slope, and Brier score [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 by decision curve analysis (DCA) to evaluate the net benefit of the model across different threshold probabilities; this analysis was an exploratory result within the same cohort [17].

2.6 Sample size estimation

ample size estimation was performed using G*Power 3.1 software[18]. This was a cross-sectional association study, and the primary objective was to compare average step width between patients with moderate-to-severe KOA with and without a history of falls. Based on preliminary experimental results, the effect size for average step width between the two groups was Cohen's $d = 0.65$. With $\alpha = 0.05$ (two-sided) and power $1 - \beta = 0.80$, the calculated minimum total sample size was 102. Considering 10% invalid data, the final sample size was set at 120 patients (60 in the fall group and 60 in the non-fall group). It should be noted that the primary objective of this study was to assess the strength of association rather than to develop a multivariable prediction model. Due to the limited sample size, the multivariable Firth regression was only a secondary analysis and included only the five pre-specified clinical confounders to control the risk of overfitting. No independent external validation was performed in this study; all internal validation results were used only to assess model stability and cannot serve as a basis for predicting future falls.

3 Results

3.1 Comparison of gait biomechanical parameters between the fall and non-fall groups in patients with moderate-to-severe osteoarthritis

Based on the results in Table 1, among patients with KL grade III KOA, those with a history of falls showed significant differences from those without a history of falls in multiple gait parameters [19-20], suggesting that an increased risk of falls is closely related to a specific gait adaptation pattern. Regarding joint range of motion, patients with a history of falls had smaller left hip range of motion (22.6° vs 31.4°, $P < 0.001$), left knee range of motion (35.5° vs 48.02°, $P < 0.001$), and left knee maximum angle (52.05° vs 57.55°, $P = 0.0073$) than those without a history of falls;

the right knee minimum angle (16.59° vs 10.65°, P < 0.001) was larger than that in patients without a history of falls [21]. 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 patients with a history of falls, while the static right posterior value (31.05 vs 26.18, P = 0.0183) was significantly higher. 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 patients with a history of falls than in those without, which may be related to poor landing control or compensatory force generation. Regarding spatiotemporal parameters, patients with a history of falls exhibited a typical "fall-risk gait": slower gait speed (0.4 m/s vs. 0.58 m/s, P < 0.001), prolonged left and right step time (725 ms vs. 638 ms, P = 0.0349; 763 ms vs. 650 ms, P < 0.001), and shortened left and right step length and stride length (e.g., left step length 28.95 vs 38.85, P = 0.0029) [22-23]. Meanwhile, left single support time (316.7 ms vs 414.3 ms, P < 0.001) was significantly shortened, while double support time (left double support: 938.55 ms vs. 542.8 ms, P < 0.001; right double support: 938.05 ms vs 558.35 ms, P < 0.001) and total support time were prolonged. In addition, 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 larger in patients with a history of falls than in those without [24]. Regarding step width, patients with a history of falls had larger left step width (22.9 cm vs. 8.85 cm, P < 0.001), right step width (22.96 cm vs 8.72 cm, P < 0.001), left foot width (14.3 cm vs 8.45 cm, P < 0.001), and right foot width (14.14 cm vs. 7.79 cm, P < 0.001) than those without a history of falls. The remaining parameters showed no statistically significant differences between groups (P > 0.05). In summary, among patients with grade III KOA, the fall group was characterized by decreased joint range of motion, slower gait speed, shortened step length, prolonged double support phase, and increased step width.

Table 1 Comparison of gait parameters between KLIII KOA patients with a history of falls and those without a history of falls

Parameter	Fall history Group	No Fall history Group	Test	P value
Left Hip Range	22.6（15.4,31.27）	31.4（27.98,38.15）	Mann–Whitney U	<0.001
Left Hip Max	43.79±12.19	47.31±8.40	t-test	0.198
Left Hip Min	18.55（11.2,23.6）	15.4（9.83,22.6）	Mann–Whitney U	0.367
Right Hip Range	26.5（21.4,31.4）	29.6（25.83,32.1）	Mann–Whitney U	0.061
Right Hip Max	46.01±13.11	46.19±10.22	t-test	0.954
Right Hip Min	18.93±12.95	14.58±9.53	t-test	0.144
Left Knee Range	35.50±13.16	48.02±11.89	t-test	<0.001
Left Knee Max	52.05（47.60,56.45）	57.55（52.62,64.27）	Mann–Whitney U	0.007

Left Knee Min	9.55（6.22,25.2）	17.85(6.05,14.6）	Mann–Whitney U	0.429
Right Foot Progression Angle	17.2 (10.33,25.5)	(9.87,21.56)	Mann–Whitney U	0.601
Right Knee Range	43.9（29.1,50.9）	48.9（37.45,53.05）	Mann–Whitney U	0.185
Left Step Width	22.9 (22.15,23.4)	8.85 (5.75,10.65)	Mann–Whitney U	<0.001
Right Knee Max	55.1（51.8,66.1）	57.6（49.6,62.3）	Mann–Whitney U	0.900
Right Step Width	22.96±1.85	8.72±3.00	t-test	<0.001
Right Knee Min	16.59±6.94	10.65±5.91	t-test	<0.001
Left Foot Width	14.3 (9.5,19)	8.45 (8.8,78)	Mann–Whitney U	<0.001
Left Ankle Range	22（17.6,26.7）	25.25（23.02,28.98）	Mann–Whitney U	0.070
Right Foot Width	14.14±6.44	7.79±1.12	t-test	<0.001
Left Ankle Max	13.1（7.50,18.23）	14.4（12.95,17.15）	Mann–Whitney U	0.258
Walking Speed	0.4±0.2	0.58±0.15	t-test	<0.001
Left Ankle Min	-10.75（-13.1,-5.1）	-10.3（-13.45,-6.17）	Mann–Whitney U	0.994
Left Step Time	725.00 (666.7,800)	638.05(614.3,716.7)	Mann–Whitney U	0.035
Right Ankle Range	20.4 (16.38,25.8)	20.9 (18.27,24.4)	Mann–Whitney U	0.584
Right Step Time	783.35(683.3,1878.5)	650 (604.18,716.7)	Mann–Whitney U	<0.001
Right Ankle Max	15.1(11.85,17.08)	13.35(10.33,17.12)	Mann–Whitney U	0.258
Right Ankle Min	-8.7 (-11.3,-0.68)	-7.3 (-11.35,-4.38)	Mann–Whitney U	0.023
Left Step Length	28.95 (16.98,36.55)	38.85 (30.88,46.12)	Mann–Whitney U	0.003
Static Left Anterior	22.47±4.43	25.79±5.70	t-test	0.014
Right Step Length	35.05 (17.18,39.6)	38.9 (35.28,46.30)	Mann–Whitney U	0.032
Static Left Posterior	27.78 (20.53,33.04)	28.90 (21.86,31.72)	Mann–Whitney U	0.865
Left Stride Length	57.1 (39.80,69.30)	75.05 (63.40,89.00)	Mann–Whitney U	<0.001
Static Right Anterior	19.27±4.30	20.65±3.76	t-test	0.191
Right Stride Length	57.1 (32.58,70.10)	74.7 (62.67,89.53)	Mann–Whitney U	<0.001
Static Right Posterior	31.05(24.8,36.61)	26.18 (21.8,29.43)	Mann–Whitney U	0.018
Left Gait Cycle	1382.1(1087.47,1750)	1275(1228.50,1566.70)	Mann–Whitney U	0.167
Dynamic Left Foot	680(466.70,760)	473.35(371.40,583.30)	Mann–Whitney U	0.033
Right Gait Cycle	1450(1229.15,1640.70)	1325(1235.67,1416.80)	Mann–Whitney U	0.060
Dynamic Right Foot	658.35(583.30,785.00)	516.7(444.60,600.08)	Mann–Whitney U	0.006
Left Single Support	316.7(212.90,307.30)	265.6(204.45,310.75)	Mann–Whitney U	0.888
Left Foot Impulse	316.7(285.00,350.00)	414.9(366.70,440.45)	Mann–Whitney U	<0.001
Right Single Support	390.74±12.88	390.72±82.63	t-test	0.259
Right Foot Impulse	390(323.32,444.65)	400 (351.78,447.30)	Mann–Whitney U	0.419
Left Foot Contact Area	137.6(121.63,141.8)	136.65(120.4,154.7)	Mann–Whitney U	0.359
Right Foot Contact Area	126.8(85.72,135.4)	128.05(118.45,147.07)	Mann–Whitney U	0.093
Left Foot Progression Angle	17.82(14.8,22.17)	13.48 (10.63,20.65)	Mann–Whitney U	0.085

Left Double Support	938.55(591.7,1575.00)	542.8(471.45,583.30)	Mann–Whitney U	<0.001
Right Double Support	938.05(620.82,1000.00)	558.35(479.18,633.30)	Mann–Whitney U	<0.001
Left Total Support	1173.35(945.80,1276.67)	921.35(827.42,1012.53)	Mann–Whitney U	<0.001
Right Total Support	1280(987.53,1440.83)	958.35(866.7,1091.67)	Mann–Whitney U	<0.001

Note: Data is expressed as mean ± standard deviation or median (interquartile range).

Based on the results in Table 2, among patients with KL grade IV KOA, those with a history of falls differed from those without a history of falls in multiple gait parameters. Regarding joint range of motion, patients with a history of falls had smaller left hip range of motion (27.95° vs 39.8°, $P < 0.001$), right hip range of motion (26.6° vs 37.5°, $P < 0.001$), left hip maximum angle (50.6° vs 54.85°, $P=0.0025$), right hip maximum angle (47.6° vs 54.55°, $P = 0.0011$), right knee range of motion (37.15° vs 46.25°, $P < 0.001$), right knee maximum angle (49.35° vs 56.45°, $P < 0.001$), and right ankle range of motion (20.15° vs 25.45°, $P < 0.001$) than those without a history of falls; left ankle range of motion was also smaller than that in patients without a history of falls (22.2° vs 27.4°, $P = 0.0463$). Regarding plantar pressure, patients with a history of falls had smaller left and right foot contact areas than those without a history of falls (129.8 cm^2 vs 147.35 cm^2, $P < 0.001$; 124.1 cm^2 vs 153.8 cm^2, $P= 0.0019$). Regarding spatiotemporal parameters, patients with a history of falls had slower gait speed (0.36 m/s vs 0.52 m/s, $P < 0.001$) [25], shorter left and right step length (25.9 cm vs 45.75 cm, $P < 0.001$; 33.5 cm vs. 38.85 cm, $P = 0.0198$), shorter left and right stride length (58.3 cm vs. 77.7 cm, $P < 0.001$; 56.05 cm vs. 74.3 cm, $P < 0.001$), shorter left single support time (381.65 ms vs. 483.35 ms, $P < 0.001$), shorter right single support time (400 ms vs 470 ms, $P < 0.001$), longer left and right double support time (800 ms vs 583.35 ms, $P < 0.001$; 785 ms vs 608.3 ms, $P< 0.001$), and longer left total support time (1191.65 ms vs. 1091.65 ms, $P = 0.0117$). Patients spent more time with both feet on the ground to maintain stability, but once they entered the single-leg support phase (the most unstable phase of walking), they were unable to maintain stability—possibly due to hip abductor weakness or pain-related reluctance to bear weight [26]. Regarding step width, patients with a history of falls had larger left step width (22.9 cm vs 10.95 cm, $P < 0.001$), right step width (22cm vs 11.65 cm, $P < 0.001$), left foot width (11.65 cm vs 8.6 cm, $P = 0.0076$), and right foot width (13.29 cm vs 8.65 cm, $P<0.001$) than those without a history of falls. The right foot progression angle was larger in patients with a history of falls than in those without a history of falls (19.76° vs 5.16°, $P < 0.001$). The remaining parameters showed no statistically significant differences between groups ($P>0.05$).

Table 2Comparison of gait parameters between KL IV KOA patients with a history of falls and those without a history of falls

Parameter	Fall history Group	No Fall history Group	Test	P value
Left Hip Range	27.95(24.60,31.70)	39.8 (35.40,42.30)	Mann–Whitney U	<0.001
Left Hip Max	50.60(42.72,54.95)	54.85(51.60,58.60)	Mann–Whitney U	0.003
Left Hip Min	21.35 (13.20,25.20)	16.15 (10.30,29.40)	Mann–Whitney U	0.463
Right Hip Range	26.60 (20.90,30)	37.50 (34.40,39.20)	Mann–Whitney U	<0.001
Right Hip Max	47.60 (40.93,53.55)	54.55 (47.80,61.10)	Mann–Whitney U	0.001
Right Hip Min	16.75 (8.60,30.00)	12.9 (6.30,21.70)	Mann–Whitney U	0.211
Left Knee Range	40.00 (29.35,46.80)	44.95 (39.30,53.30)	Mann–Whitney U	0.141
Left Knee Max	51.60 (46.12,58.70)	55.25 (48.00,60.30)	Mann–Whitney U	0.211
Left Knee Min	11.90 (9.62,19.75)	11.90 (6.40,17.30)	Mann–Whitney U	0.888
Right Knee Range	37.15 (29.35,44.90)	46.25 (40.60,56.70)	Mann–Whitney U	<0.001
Right Knee Max	49.35 (38.15,54.30)	56.45 (48.00,71.20)	Mann–Whitney U	<0.001
Right Knee Min	12.40 (6.90,18.50)	14.60 (10.90,16.70)	Mann–Whitney U	0.509
Left Ankle Range	22.20 (19.00,26.30)	27.40 (20.20,29.90)	Mann–WhitneyU	0.046
Left Ankle Max	14.85 (10.00,16.42)	13.40 (11.30,25.40)	Mann–Whitney U	0.662
Left Ankle Min	-9.90 (-13.12,-5)	-9.3 (-13.50,-7.60)	Mann–Whitney U	0.888
Right Ankle Range	20.15 (17.20,22.00)	25.45 (22.00,30.10)	Mann–Whitney U	<0.001
Right Ankle Max	12.35 (10.20,14.80)	12.35 (10.60,14.80)	Mann–Whitney U	0.773
Right Ankle Min	-9.10 (-11.80,-4.70)	-10.8 (-14.30,-7.00)	Mann–Whitney U	0.121
Static Left Anterior	24.50 (18.19,29.99)	26.78 (22.56,27.70)	Mann–Whitney U	0.162
Static Left Posterior	28.76 (22.53,33.63)	24.94(23.24,27.58)	Mann–Whitney U	0.141
Static Right Anterior	21.31 (20.56,23.88)	20.98 (18.60,24.06)	Mann–Whitney U	0.211
Static Right Posterior	25.80 (19.26,32.23)	26.28 (24.74,28.60)	Mann–Whitney U	0.717
Dynamic Left Foot	608.30 (533.30,770.80)	557.15(400.00,716.70)	Mann–Whitney U	0.140
Dynamic Right Foot	763.30 (533.30,783.30)	675.00 (528.60,716.70)	Mann–Whitney U	0.829
Left Foot Impulse	323.60 (268.15,376.10)	349.65(312.5,423.70)	Mann–Whitney U	0.105
Right Foot Impulse	290.95 (245.60,340.50)	264.80(188.40,354.40)	Mann–Whitney U	0.239
Left Foot Contact	129.80 (118.12,148.75)	147.35(137.60,166.10)	Mann–Whitney	<0.001

Area			U	
Right Foot Contact Area	124.10 (116.78,137.80)	153.8(126.80,160.90)	Mann–Whitney U	0.002

(Continued)Table 2. Comparison of gait parameters between KL IV KOA patients with a history of falls and those without a history of falls

Left Foot Progression Angle	20.37 (11.95,27.02)	16.59 (2.71,24.91)	Mann–Whitney U	0.122
Right Foot Progression Angle	19.76 (14.08,25.72)	5.16 (1.44,9.36)	Mann–Whitney U	<0.001
Left Step Width	22.90 (22.00,23.50)	10.95 (7.20,18.10)	Mann–Whitney U	<0.001
Right Step Width	22.00 (21.80,23.10)	11.65 (7.20,18.90)	Mann–Whitney U	<0.001
Left Foot Width	11.65 (7.20,13.40)	8.60 (7.90,8.70)	Mann–Whitney U	0.008
Right Foot Width	13.29(12.20,14.10)	8.65 (6.70,9.50)	Mann–Whitney U	<0.001
Walking Speed	0.36（0.26，0.43）	0.52（0.43,0.63)	Mann–Whitney U	<0.001
Left Step Time	766.70（716.70,920.00)	766.65（671.4,833.3)	Mann–Whitney U	0.183
Right Step Time	741.65（733.30,820.00)	758.35（750.00,828.50)	Mann–Whitney U	0.375
Left Step Length	25.90（21.30,34.10)	45.75（41.10,48.00)	Mann–Whitney U	<0.001
Right Step Length	33.50 (28.20,37.12)	38.85 (35.80,47.20)	Mann–Whitney U	0.019
Left Stride Length	58.30 (46.50,65.50)	77.70 (68.60,96.80)	Mann–Whitney U	<0.001
Right Stride Length	56.05 (48.38,66.30)	74.30 (68.60,80.80)	Mann–Whitney U	<0.001
Left Gait Cycle	1500（1420.85,1572.50)	1525.00（1499.90,1666.70)	Mann–Whitney U	0.303
Right Gait Cycle	1550（1450.00,1591.67)	1536.90（1500.00,1583.30)	Mann–Whitney U	0.859
Left Single Support	381.65（350.00,450.00)	483.35（428.60,550.00)	Mann–Whitney U	<0.001
Right Single Support	400.00（295.00,450.00)	470.00（433.30,483.30)	Mann–Whitney U	<0.001
Left Double Support	800.00（616.70,833.30)	583.30（533.30,671.40)	Mann–Whitney U	<0.001
Right Double Support	785.00（616.70,883.30)	608.30（560.00,633.30)	Mann–Whitney U	<0.001
Left Total Support	1191.60（1045.80,1300.00)	1091.65（1028.50,1150.00)	Mann–Whitney U	0.012
Right Total Support	1120.00（1066.70,1216.70)	1083.35（1066.70,1183.30)	Mann–Whitney U	0.209

Note: Data is expressed as mean ± standard deviation or median (interquartile range).

3.2 Results of two-way ANOVA (main and interaction effects of KL grade and fall status)

To investigate the effects of KOA severity (KL grade: III vs IV) and fall history (yes vs no) on gait characteristics, two-way ANOVA was used to examine the main and interaction effects for each gait parameter. The significance level was adjusted by FDR correction, and a corrected $P < 0.05$ was considered statistically significant.Main effects: KL grade showed significant main effects on multiple gait parameters, including right foot progression 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 maximum angle ($F= 8.817$, $P < 0.05$), right hip range of motion ($F=6.863$, $P < 0.05$), left foot impulse ($F= 20.879$, $P< 0.001$), static right anterior ($F=8.064$, $P<0.05$), and left hip maximum angle ($F=14.417$, $P < 0.05$), suggesting that KL grade mainly affects lateral stability, hip range of motion, and foot contact characteristics. The main effect of fall history was more extensive, with significant main effects on right foot progression angle ($F= 21.067$, $P < 0.001$), right step width ($F= 318.066$, $P < 0.001$), left step width ($F = 340.655$, $P < 0.001$), right step time ($F=13.64$, $P < 0.001$), right foot width ($F=36.889$, $P < 0.001$), left step length ($F=29.53$, $P < 0.001$), right step length ($F=6.945$, $P < 0.05$), left single support ($F=34.031$, $P < 0.001$), left double support ($F = 17.124$, $P< 0.001$), left total support ($F=18.017$, $P < 0.001$), left stride length ($F=33.955$, $P < 0.001$), right stride length ($F=32.725$, $P < 0.001$), left knee range of motion ($F=11.765$, $P < 0.05$), right knee range of motion ($F=14.119$, $P < 0.001$), left hip range of motion ($F=8.637$, $P < 0.05$), left hip maximum angle ($F= 6.242$, $P < 0.05$), right hip maximum angle ($F=7.859$, $P < 0.05$), right hip range of motion ($F = 8.175$, $P < 0.05$), dynamic right foot ($F = 6.387$, $P < 0.05$), static left anterior ($F=9.1$, $P < 0.05$), right foot contact area ($F= 9.083$, $P < 0.05$), right double support ($F=10.982$, $P < 0.05$), and right foot impulse ($F=19.033$, $P < 0.001$), indicating that fall history had a more pronounced overall effect on gait patterns.Interaction effects: Significant interaction effects between KL grade and fall history were observed for right foot progression angle ($F=16.339$, $P< 0.001$), right step width ($F=14.8$, $P < 0.05$), right knee minimum angle ($F = 10.131$, $P < 0.05$), right knee maximum angle ($F= 10.101$, $P < 0.05$), left step width ($F= 9.96$, $P < 0.05$), right step time ($F= 9.05$, $P < 0.05$), and right hip maximum angle ($F=7.655$, $P < 0.05$) [27-28]. No significant interaction effects were observed for the remaining parameters (corrected $P > 0.05$). These results suggest that KL grade and fall history have a joint effect on some gait parameters; however, the specific pattern should be interpreted cautiously given the cross-sectional design, as shown in Table 3.

Table3 The Two Factor ANOVA Results of KL Grading and Fall History on Gait Parameters

Gait Parameters	KLgrade	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	14.800	＜0.05
Right Knee Min	1.276	0.429	0.445	0.549	10.131	＜0.05
Right Knee Max	2.784	0.221	4.765	0.051	10.101	＜0.05
Left Step Width	9.863	＜0.05	340.655	＜0.001	9.960	＜0.05
Right Step Time	0.774	0.556	13.640	＜0.001	9.050	＜0.05
Right Hip Max	8.817	＜0.05	7.859	＜0.05	7.655	＜0.05
Right Ankle Range	0.450	0.648	0.047	0.846	6.841	0.064
Right Hip Range	6.863	＜0.05	8.175	＜0.05	5.947	0.083
Left Foot Contact Area	2.742	0.221	10.595	＜0.05	5.603	0.087
Left Hip Min	5.176	0.079	1.286	0.357	5.508	0.087
Left Step Length	4.779	0.087	29.530	＜0.001	5.381	0.087
Right Knee Range	0.098	0.856	14.119	＜0.001	4.653	0.120
Right Hip Min	4.776	0.087	7.000	＜0.05	4.139	0.150
Left Foot Impulse	20.879	＜0.001	3.321	0.113	3.953	0.157
Right Single Support	5.352	0.076	12.649	＜0.05	3.818	0.159
Left Foot Width	2.968	0.221	20.178	＜0.001	3.373	0.193
Static Right Posterior	1.487	0.396	1.772	0.263	3.300	0.193
Static Right Anterior	8.064	＜0.05	0.138	0.740	3.009	0.209
Left Hip Max	14.417	＜0.05	6.242	＜0.05	2.990	0.209
Left Knee Range	0.156	0.811	11.765	＜0.05	2.460	0.277
Right Step Length	0.031	0.915	6.945	＜0.05	2.290	0.295
Left Step Time	2.766	0.221	3.103	0.123	2.049	0.305
Left Knee Min	1.092	0.475	0.644	0.503	2.043	0.305
Left Total Support	1.343	0.423	18.017	＜0.001	2.035	0.305
Left Ankle Range	0.737	0.556	0.006	0.938	1.937	0.305
Left Ankle Min	2.175	0.284	0.976	0.405	1.783	0.324
Right Ankle Max	2.685	0.221	1.136	0.384	1.485	0.383
Right Foot Contact Area	6.120	0.054	9.083	＜0.05	0.928	0.524
Right Stride Length	1.683	0.371	32.725	＜0.001	0.908	0.524

Left Hip Range	11.692	＜0.05	8.637	＜0.05	0.864	0.524
Left Foot Progression Angle	0	0.991	3.073	0.123	0.853	0.524
Left Double Support	0.336	0.700	17.124	＜0.001	0.847	0.524
Left Ankle Max	0.074	0.857	1.111	0.384	0.680	0.583
Dynamic Right Foot	2.155	0.284	6.387	＜0.05	0.644	0.584
Left Knee Max	0.150	0.811	12.895	＜0.05	0.564	0.606
Walking Speed	0.644	0.584	0.730	0.479	0.541	0.606
Right Ankle Min	1.044	0.477	0.168	0.725	0.479	0.625
Right Foot Width	0.072	0.857	36.889	＜0.001	0.392	0.650
Static Left Anterior	0.440	0.648	9.100	＜0.05	0.387	0.650
Static Left Posterior	0.442	0.648	1.034	0.397	0.221	0.753
Left Gait Cycle	0.184	0.811	0.455	0.549	0.205	0.753
Right Double Support	0.003	0.979	10.982	＜0.05	0.184	0.753
Right Gait Cycle	0.009	0.962	0.499	0.546	0.157	0.753
Left Single Support	21.060	＜0.001	34.031	＜0.001	0.155	0.753
Right Foot Impulse	19.033	＜0.001	2.600	0.159	0.033	0.911
Dynamic Left Foot	3.659	0.156	5.167	＜0.05	0.022	0.917
Left Stride Length	1.635	0.371	33.955	＜0.001	0.006	0.959
Right Total Support	0.740	0.556	0.523	0.546	0.001	0.979

Note: ANOVA, analysis of variance; KL, Kellgren-Lawrence。

The results of two-way ANOVA in Table 3 showed that KL grade and fall history had significant interaction effects on multiple gait parameters. To further illustrate the patterns of these interaction effects, left and right step width, right foot progression angle, right stance time, right hip maximum angle, and right knee maximum angle were selected for visualization, as shown in Figures 1–3. Figure 1 shows the interaction effect for left and right step width. In patients with KL grade III, the left and right step widths were both relatively high in the fall history group, whereas step width was smaller in the no-fall group. In patients with KL grade IV, step width in the no-fall group increased compared with grade III, but step width in the fall history group remained at a high level and was significantly larger than that in the no-fall group. KL grade and fall history showed significant interaction effects on both left step width ($P < 0.05$) and right step width ($P< 0.05$). Figure 2A shows the interaction effect for right stance time. In patients with KL grade III, right stance time was shorter in the fall history group than in the no-fall group; however, in patients with KL grade IV, this trend reversed, with right stance time being longer in the fall history

group than in the no-fall group. KL grade and fall history showed a significant interaction effect on right stance time ($P < 0.05$). Figure 2B shows the interaction effect for right foot progression angle. In patients with KL grade III, there was no obvious difference in right foot progression angle between the fall history and no-fall groups; however, in patients with KL grade IV, right foot progression angle decreased in the no-fall group compared with grade III, whereas it increased markedly in the fall history group. Two-way ANOVA confirmed a significant interaction effect between KL grade and fall history on right foot progression angle ($P < 0.001$). Figure 3A shows the interaction effect for right hip maximum angle. In the no-fall group, right hip maximum angle was larger in patients with KL grade IV than in those with grade III; however, in the fall history group, right hip maximum angle remained at a relatively low level in both KL grade III and IV patients, with no obvious difference between the two groups. KL grade and fall history showed a significant interaction effect on right hip maximum angle ($P< 0.05$). Figure 3B shows the interaction effect for right knee maximum angle. In the no-fall group, right knee maximum angle decreased slightly from KL grade III to IV. In patients with KL grade III, right knee maximum angle was slightly higher in the fall history group than in the no-fall group; however, in patients with KL grade IV, this difference disappeared. KL grade and fall history showed a significant interaction effect on right knee maximum angle ($P< 0.05$). These findings suggest that as KOA progresses to an advanced stage, any compensatory adjustments in joint motion present at earlier stages may become ineffective, and generalized restriction of joint function becomes predominant.

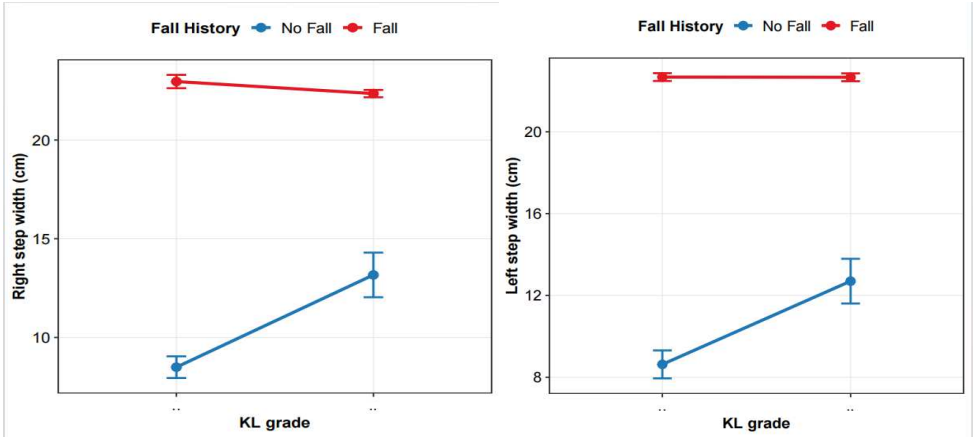


Figure 1 Interaction diagram of left and right step widths

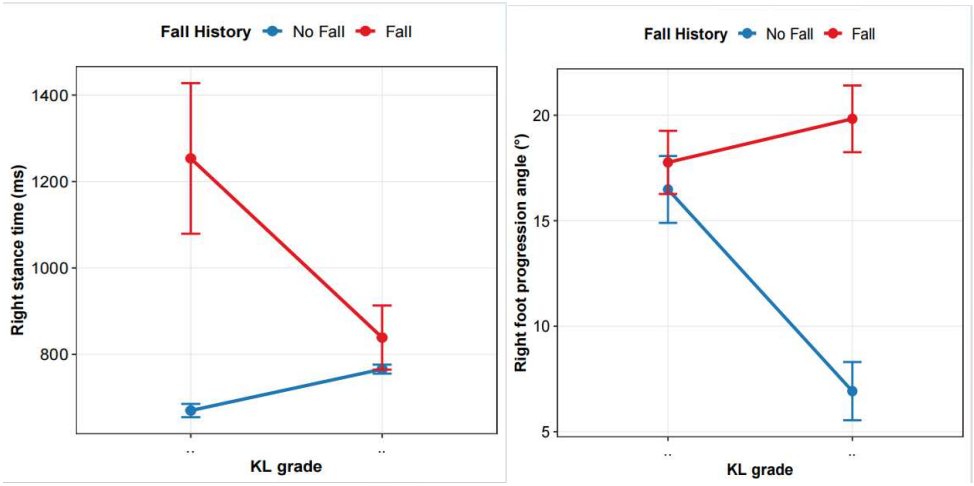


Figure 2 Interaction diagram between right step time and right foot progression angle

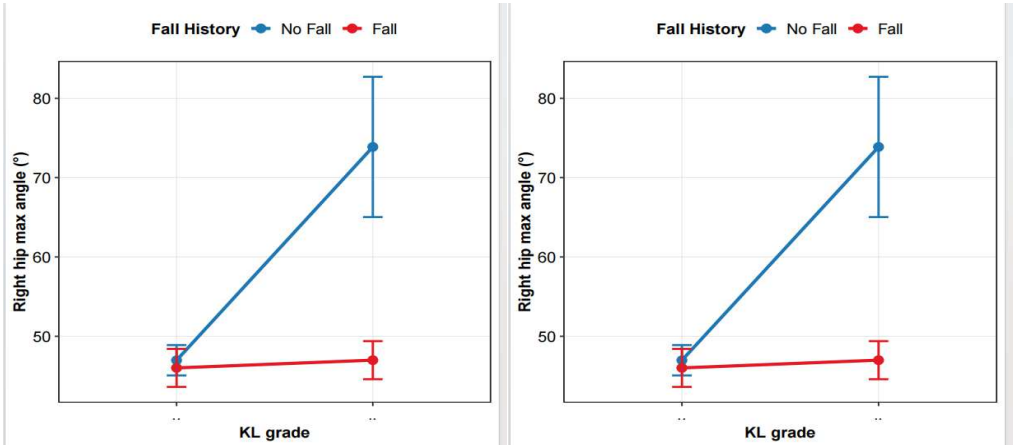


Figure3 Interaction diagram of maximum angle of right hip and maximum angle of right knee

3.3 Exploratory variable screening and identification of core variables

To preliminarily explore the associations between gait parameters and a history of falls and to inform the subsequent primary model, exploratory analyses were first performed. Univariate Firth's penalized-likelihood regression was used to screen 20 gait parameters. The results showed that 14 variables, including left step width (OR= 2.386, P< 0.001), right step width (OR=1.841, P< 0.001), and left step length (OR=0.919, P<0.001), were significantly associated with a history of falls (Supplementary Table S1). Gait speed did not reach statistical significance in the univariate analysis (OR=0.849, P=0.507). To avoid multicollinearity and assess the stability of variable selection, LASSO regression with 10-fold cross-validation (Supplementary Figure S1) combined with bootstrap (1,000 resamples) was further used to calculate the selection frequency of each variable (Supplementary Tables S2 and S3). The results showed that the selection frequency was 100% for left step width,

99.8% for fear of falling, and 96.7% for left foot progression angle; in contrast, the selection frequencies for left step length (0.3%) and gait speed (11.9%) were extremely low. These findings suggest that step width and its related indicators are highly stable in discriminating a history of falls, whereas the effects of step length and gait speed in the model are highly unstable and susceptible to sample fluctuations. It should be emphasized that the above exploratory screening results were used only to generate hypotheses and to identify the primary exposure variable, and were not directly used for the construction of the final model. To avoid the risk of overfitting caused by data-driven selection, the primary association analysis (Section 3.4) strictly used pre-specified average step width as the primary exposure variable and adjusted for pre-specified clinical confounders, without including other unstable variables selected by LASSO.

3.4 Independent association between average step width and history of falls

Building on the exploratory analysis, a pre-specified primary association analysis was performed in this study. With a history of falls within the past year as the dependent variable and average step width as the primary exposure variable, five clinical confounders were adjusted for: age, sex, BMI, KL grade, and walker use. Because fear of falling has an obvious reverse causal relationship with fall history (falls lead to fear), it was excluded from the adjusted model. Because average step width showed quasi-complete separation between the two groups (step width concentrated at 20.65–25.10 cm in the fall group and 3.35–22.75 cm in the no-fall group, with minimal overlap), ordinary maximum likelihood estimation failed. Therefore, Firth's penalized-likelihood logistic regression was used for multivariable analysis. Collinearity diagnostics showed that the variance inflation factor (VIF) for all variables was < 5.

The results are shown in Table 4. In the unadjusted model, average step width was significantly associated with a history of falls (OR= 2.243, 95% CI: 1.577–3.905, $P < 0.001$). After adjusting for age, sex, BMI, KL grade, and walker use, the association remained robust (OR= 2.968, 95% CI: 1.714–8.492, $P < 0.001$). In the simplified model incorporating left step length, average step width remained independently associated (OR = 3.103, 95% CI: 1.722–., $P < 0.001$), whereas left step length did not reach statistical significance (OR = 1.005, $P = 0.1664$). It is worth noting that, because of the minimal overlap in step width between the two groups, although Firth regression provided a convergent point estimate, the standard error was relatively large, resulting in wide confidence intervals (especially the upper limit). Therefore, the above OR values represent an "increase in the odds of a history of falls" rather than an absolute risk or the probability of predicting future falls. These results suggest that average step width

is the most robust independent correlate of a history of falls in patients with moderate-to-severe KOA, supporting its use as a core candidate variable for subsequent prospective studies.

Table 4.Firth regression analysis of the association between average step width and past history of falls in patients with moderate to severe knee osteoarthritis

variable	ModelA (Unadjusted)	Model B (Adjusted, final)	Model C (Simplified, final)
Avg step width	2.24 (1.58–3.91)	2.97 (1.71–8.49)	3.10 (1.72–)
age		1.08 (0.93–1.29)	1.09 (0.95–15.10)
sex		0.59 (0.03–11.17)	0.40 (0.00–9.62)
bmi		1.11 (0.70–1.75)	1.11 (0.00–1.93)
Kl grade IV		0.05 (0.00–0.76)	0.01 (0.00–0.39)
walker		24.88 (2.77–956.56)*	39.95 (3.90–)
Left step length			1.01 (1.00–1.13)

Note: Model A was the unadjusted model; Model B was adjusted for age, sex, BMI, KL grade, and walker use; Model C additionally included left step length based on Model B. Because average step width showed "quasi-complete separation" between the two groups (approximately 22–23 cm in the fall group and 8–10 cm in the no-fall group, with minimal overlap), although Firth's penalized-likelihood regression provided stable point estimates (OR) and significance (P values), it resulted in extremely wide confidence intervals or an inability to precisely calculate the upper limit (indicated by "–"). Therefore, the above results should be interpreted as an increase in the odds of a history of falls, rather than an absolute risk.

We plotted an exploratory heatmap to visualize the probability of a history of falls. The heatmap intuitively showed that when average step width exceeded 18 cm and left step length was less than 35 cm, the probability of a history of falls exceeded 0.75 (red area); conversely, when step width was less than 12 cm and step length was greater than 45 cm, the probability was lower than 0.25 (blue area).

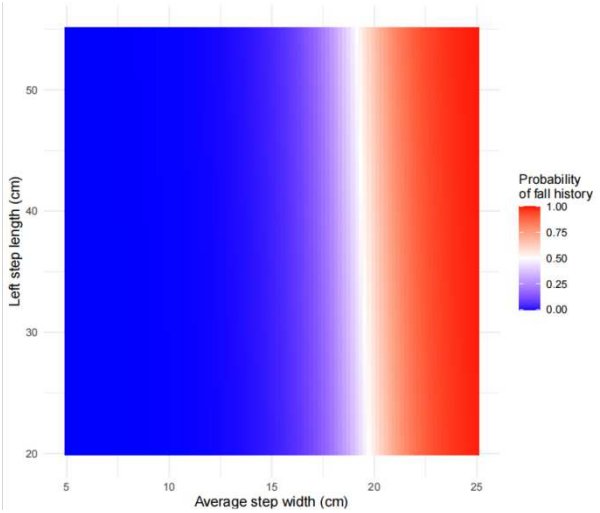


Figure 4 Exploratory visualization of the probability of a history of falls based on average step width and left step length.

Note: Exploratory visualization of the probability of a history of falls based on average step width and left step length. The x-axis represents average step width (cm), and the y-axis represents left step length (cm). The color gradient indicates the probability of a history of falls (blue: low probability; red: high probability). The color boundary is approximately located at an average step width of 18–19 cm. Due to the quasi-complete separation of average step width in this study, this figure is only an exploratory visualization within the same cohort and cannot be directly used as a tool for clinical risk stratification; the 18 cm reference threshold requires prospective external validation.

3.5 Internal validation and exploratory clinical benefit

Based on the robust associative indicator identified in the multivariable Firth regression—average step width—a univariable Firth logistic regression model was constructed. The model fit showed that for each 1 cm increase in average step width, the OR for its association with a history of falls was 2.24 (95% CI: 1.58–3.91, $P < 0.001$) [29]. Bootstrap internal validation (1,000 resamples) was used to assess model stability and optimism. The results showed that the sign consistency of the average step width regression coefficient was 100%, the optimism-corrected AUC was 0.958 (95% CI: 0.916–0.995), the calibration slope was 0.986, and the Brier score was 0.0473. The calibration curve (Figure5) showed that the predicted probabilities were highly consistent with the observed probabilities (mean absolute error = 0.019), with no obvious overfitting (see Table 5 in the main text) [30]. The AUC of leave-one-out cross-validation (LOOCV) was 0.956 (95% CI: 0.916–0.995), further confirming the generalizability of the model. Decision curve analysis (DCA) showed that within the threshold probability range

of 0.01–0.7, the net benefit of the step width-based model was significantly higher than that of the "treat all" or "treat none" strategies. For example, at a threshold probability of 0.2, the net benefit was approximately 0.45, which theoretically means that 45 additional patients who would truly experience falls could be correctly identified per 100 patients. It should be particularly emphasized that the above internal validation metrics were very high (AUC > 0.95), mainly because the step width distributions of the two groups had minimal overlap (quasi-complete separation), which may lead to overestimation of discrimination metrics. In addition, because this study had a cross-sectional design and fall history was collected retrospectively, the model cannot be used to predict future falls. The net benefit shown by DCA represents only an exploratory result based on the existing data. Therefore, the reference threshold of approximately 18 cm in this study is only hypothesis-generating and cannot be directly used as a clinical high-risk threshold, nor can it be recommended to initiate fall prevention interventions based solely on step width. As a low-cost and easily accessible candidate indicator, the true clinical value of step width still requires external validation in multicentre, prospective cohort studies.

Table 5 Summary of Internal Validation Performance of Single Variable Firth Logistic Regression Model

Indicator	Value
OR (95% CI)	2.24 (1.58–3.91)
Optimism-corrected AUC (95% CI)	0.958 (0.916–0.995)
Calibration slope	0.986
Brier Score	0.0473
LOOCV AUC (95% CI)	0.956 (0.916–0.995)
LOOCV accuracy / sensitivity / specificity	95.8% / 100% / 91.7%
Sign consistency of average step width coefficient	100%

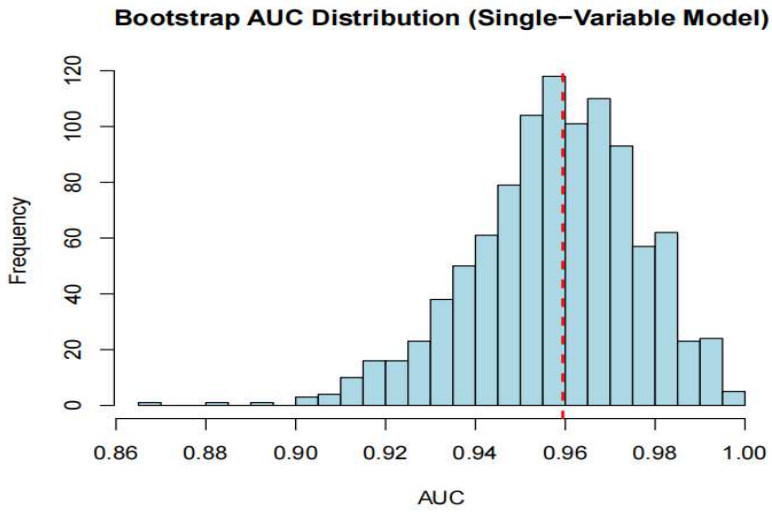


Figure 5

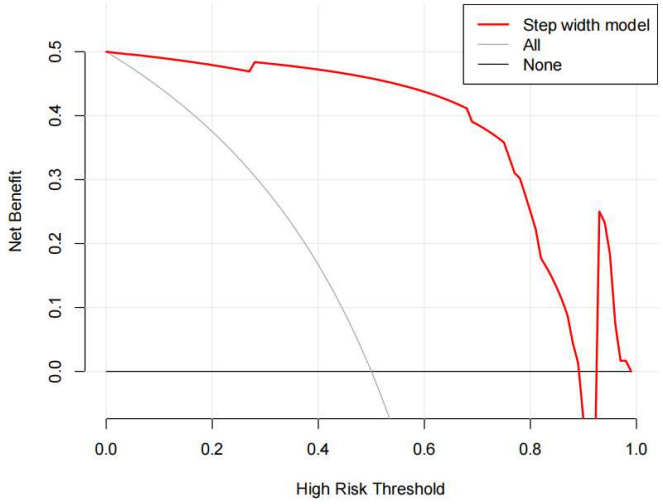


Figure 6

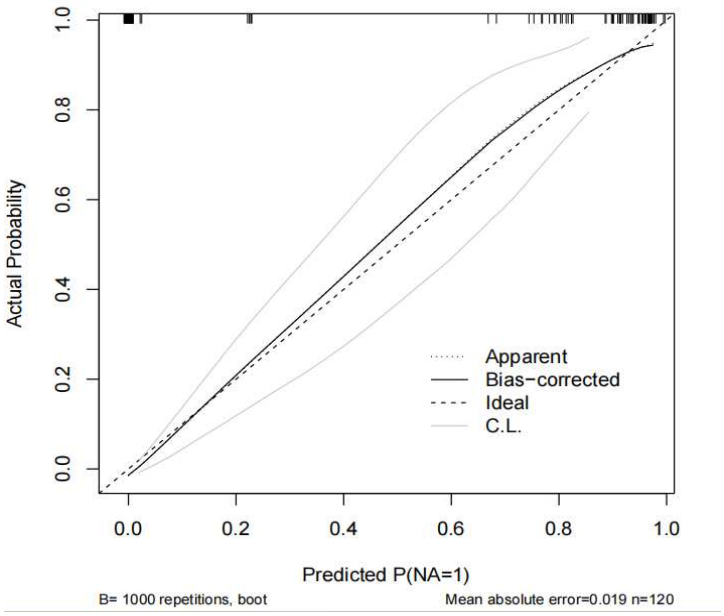


Figure 7

4. Discussion

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

This cross-sectional study compared the gait characteristics of patients with moderate-to-severe KOA with and without a history of falls. The results showed that patients with a history of falls had a significantly larger average step width than those without, accompanied by slower gait speed, shortened step length, prolonged double support time, and restricted joint range of motion. These findings are consistent with previous studies, in which patients with KOA adopt a cautious, protective gait strategy to increase walking stability, while sacrificing gait flexibility, which may paradoxically increase fall risk [31-32]. After adjusting for age, sex, BMI, KL grade, and walker use, average step width remained independently associated with a history of falls (OR=2.97, 95% CI: 1.71–8.49, $P < 0.001$). Left step length was negatively associated with a history of falls in some models, but its stability across different models and internal validation was insufficient. It should be emphasized that this study had a cross-sectional design and fall history was collected retrospectively; therefore, the results can only indicate an association between average step width and a history of falls, and cannot infer that step width is a cause of falls or that step width can predict future falls.

4.2 Interaction effects between KL grade and fall history

The interaction effects identified by two-way ANOVA revealed key clinical insights. Among patients with KL grade IV, those with a history of falls had a significantly increased foot progression angle compared with those without, whereas the trend toward increased step width was attenuated. This suggests that as arthritis progresses to grade IV, patients' compensatory ability to maintain lateral stability may be partially lost due to declined neuromuscular control. Fall events themselves may accelerate the deterioration of gait strategies, forming a vicious cycle—this is consistent with an exploratory study in BMC Musculoskeletal Disorders on falls following balance perturbation in patients with KOA [33] .

4.3 Comparison with previous studies

Previous studies on fall risk in patients with KOA have mostly focused on gait speed, step length, stance time, and joint range of motion. Slower gait speed and shortened step length are generally regarded as manifestations of cautious or protective gait, but the ability of these parameters to discriminate a history of falls is inconsistent. Step width, as a direct indicator of frontal plane stability, has been studied in older adults and patients with neurological diseases, but has rarely been reported in patients with moderate-to-severe KOA. Previous biomechanical studies suggest that widening step width can enlarge the base of support and reduce medio-lateral displacement of the center of mass, thereby maintaining lateral stability. The results of this study are partially consistent with this view: patients with moderate-to-severe KOA and a history of falls exhibited a markedly increased average step width. However, step width showed quasi-complete separation between the two groups, with approximately 22–23 cm in the fall group and 8–10 cm in the no-fall group, suggesting that two distinctly different gait strategies may exist in this population. Consistent with systematic reviews by Branco et al. and Paterson et al., patients with KOA exhibit multiple gait abnormalities associated with a history of falls; however, this study further suggests that average step width may be a noteworthy and easily measured candidate associative indicator in patients with moderate-to-severe KOA..

4.4 Biomechanical and clinical interpretation of step width

Increased step width may reflect multiple mechanisms. From a biomechanical perspective, step width directly reflects lateral stability during walking—widening step width can reduce medio-lateral displacement of the center of mass and is a common conservative gait strategy [34]. First, patients with moderate-to-severe KOA often have hip abductor weakness, knee pain, and decreased proprioception; widening step width can serve as a compensatory strategy to increase lateral stability. Second, fear of falling may lead patients to voluntarily adopt a more conservative gait, manifesting as increased step width, slower gait speed, and prolonged double support time. Third, increased foot progression angle and lower limb kinematic chain

disorders may also contribute to increased step width measurements. Fourth, fall events themselves may lead to fear and avoidance behaviors, thereby altering gait; therefore, reverse causality cannot be excluded. Two-way ANOVA also showed that KL grade and fall history had interaction effects on multiple gait parameters, suggesting that arthritis severity may affect patients' compensatory ability. However, step width showed quasi-complete separation between the two groups in this study, resulting in considerable uncertainty in effect size estimation and a wide upper limit of the 95% CI. Therefore, the above interpretations should be regarded as hypotheses rather than established mechanisms. Our contribution lies in being the first to quantify the strength of association between step width and a history of falls in patients with moderate-to-severe KOA and to verify its robustness.

4.5 Clinical significance and application value

The clinical significance of this study lies in the fact that average step width measurement is simple, economical, and reproducible, and does not require expensive equipment; it may be suitable as a candidate indicator for identifying patients with KOA and a history of falls in primary care and community settings. However, it must be emphasized that the reference threshold of approximately 18 cm in this study was derived from the same cohort and from data with quasi-complete separation; its sensitivity, specificity, and decision curve net benefit may be overestimated. Therefore, it cannot currently be recommended to use "average step width > 18 cm" directly as a clinical high-risk threshold, nor to initiate fall prevention interventions based solely on step width. In clinical practice, comprehensive assessment should still integrate detailed fall history, muscle strength, balance function, medication use, vision, and home environment. Step width may serve as a valuable candidate variable in future prospective studies, rather than an independent clinical decision-making tool.

4.6 Limitations and future directions

This study has the following limitations: (1) all samples were from a single centre, which may introduce selection bias [35]; (2) step width showed quasi-complete separation between the two groups, resulting in uncertainty in the estimated strength of association and precluding its use as a clinical risk stratification tool at present; (3) the cross-sectional design cannot determine the temporal sequence between step width and fall history, and causality cannot be distinguished; (4) fall history was collected retrospectively, which may introduce recall bias; (5) average step width showed quasi-complete separation between the two groups, and ordinary logistic regression failed; although Firth's penalized-likelihood regression provided stable point estimates, the confidence intervals were wide, and the AUC and sensitivity may be overestimated; (6) gait variability, muscle activation patterns, proprioception, number of falls, direction of falls, and home environment were not included as potentially

important factors, and the sample size was estimated based on univariate association, which is insufficient for developing a multivariable prediction model. Future multicentre, prospective cohort studies should be conducted to standardize the recording of fall events, incorporate variables such as step width variability, hip abductor muscle strength, and fear of falling, and validate the strength of association and candidate thresholds of step width in independent populations.

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 individual participants included in the study. All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

5.2 Consent for publication

Not applicable.

5.3 Availability of data and materials

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

5.4 Competing interests

The authors declare that they have no competing interests.

5.5 Funding

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5.6 Acknowledgements

None.

5.7 Clinical trial number

Not applicable.

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