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Comparison of the asymmetries in foot posture, gait and plantar pressure between patients with unilateral and bilateral knee osteoarthritis based on a cross-sectional study

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This study aimed to observe the characteristics of foot posture asymmetry and abnormal gait in patients with unilateral and bilateral knee osteoarthritis (KOA) and to explore the association between foot posture asymmetry, abnormal gait and the clinical symptoms and severity of KOA. Sixty patients with KOA were allocated as follows: unilateral group (UG; $n = 30$) and bilateral group (BG; $n = 30$). We accessed foot posture, foot posture asymmetry, gait and plantar pressure parameters and symmetry index, clinical symptom-related scores and disease severity, and investigated the relationship between these variables. The results showed that the overall percentage of asymmetry and severe asymmetry in foot posture were lower in BG than in UG. There was substantial asymmetry in many gait indicators within the two groups, but no significant differences were observed between the two groups. Moreover, foot posture asymmetry, multiple gait and plantar pressure parameters and symmetry indices were closely related to clinical symptoms and disease severity. In conclusion, both unilateral and bilateral KOA patients have foot posture asymmetry and gait asymmetry, but the foot posture asymmetry of the former is more severe than that of the latter. Intervention for this population should treat simultaneously both knee joints. The evaluation and monitoring of foot posture asymmetry, gait and plantar pressure parameters and symmetry indices can provide a more comprehensive and scientific basis for the prevention and treatment of KOA.

Keywords Knee osteoarthritis, Foot posture, Gait, Plantar pressure, Asymmetry

Knee osteoarthritis (KOA) is a common, chronic degenerative joint disease affecting older adults, the foremost cause of lower limb disability among the elderly in the whole world[1,2]. The primary aims in the treatment of KOA are relieving symptoms and slowing the progression of the disease, and treatment options include physical therapy, medication, orthopedic aids, and finally, surgery[3–5]. With the aging of the population and the rising prevalence of obesity and multimorbidity, the prevalence of KOA is expected to rise[6], which will impose a substantial burden to both individuals and healthcare system[7]. Although several risk factors for the development of KOA have been identified[8], the etiology of KOA remains unclear, and it is important to further investigate the modifiable potential risk factors for KOA.

The changes of mechanical properties of adjacent joints could affect the development of KOA[9], and the foot and ankle play an important role in the biomechanical changes of lower extremities in patients with KOA[10], so foot/ankle posture deformities are considered as potential determinants contributing to KOA. Foot posture index (FPI) could effectively evaluate foot posture and classify the foot into pronation, neutral and supination[11]. Compared with traditional measurement methods[12], footprints[13] and automatic measurement instruments[14], it has been proved to be a reliable, simple and economical method. Any abnormality of foot posture (either as

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pronation or supination) may affect the force distribution of the whole lower limb (including knee joint), and then change the adduction torque of knee joint, which leads to the occurrence of KOA[15]. Several studies have shown that foot posture assessed by FPI is closely related to pain and function in patients with KOA[15], and that patients with medial compartment KOA have a more pronated foot posture compared with healthy subjects[16]. Additionally, there is evidence that foot posture asymmetry is associated with lower extremity function[17]. Our previous studies[18,19] have also found that foot posture asymmetry in patients with KOA was more severe than that in healthy individuals and was positively correlated with the K-L grade of KOA. However, foot posture asymmetry in patients with unilateral and bilateral KOA is still rarely reported.

There is evidence that abnormal gait is closely related to KOA[20,21]. Gait analysis technology is a method that mainly uses equipment such as force measurement platforms to collect and calculate the lower limb kinematics, kinetics and other information of the patient[22,23]. The plantar pressure analysis is part of the generalized gait analysis, which can evaluate the force points of the patient's lower limbs by measuring the plantar pressure of different subdivisions of the sole. Combining the two can comprehensively and dynamically evaluate the dynamic changes in the biomechanics of the patient's lower limbs[22,23]. Several studies have demonstrated that many gait spatiotemporal and plantar pressure parameters in patients with KOA are different from those in healthy subjects[24–27], and some parameters are significantly correlated with the severity and pain level of KOA[20,21,28]. However, there is still insufficient clinical evidence to determine whether unilateral and bilateral KOA lead to similar gait changes. A study[29] showed that similar functional performance and perception of functional ability between patients with unilateral and bilateral KOA. In contrast, another study[30] indicated that patients with unilateral KOA presented with asymmetric gait, whereas patients with bilateral KOA had a symmetrical gait. Data from a recent cohort study[31] demonstrated that 80% of patients with unilateral KOA would develop bilateral knee disease within 12 years. Therefore, it is unclear whether patients with unilateral KOA who have symptoms in only one knee should treat both knees simultaneously.

Additionally, many studies have also reported that foot posture is associated with gait spatiotemporal and plantar pressure parameters[32–35]. Specifically, several studies[32,33] demonstrated that compared with control subjects with normal FPI, the stride length and stride time of each foot, gait cycle duration, and cadence of pronation subjects were significantly changed. Additionally, participants with cavus feet had significantly lower plantar weight-bearing area, and plantar pressure of the whole forefoot area except metatarsal bone increased significantly. Other studies have also indicated that higher pressure-time in rearfoot, forefoot and the plantar surface of the whole foot in cavus feet compared to normal feet[34], and greater planus foot posture was associated with increasing peak plantar pressure across the entire foot in the elderly[35]. However, few studies have examined whether foot posture asymmetry is related to gait spatiotemporal and plantar pressure parameters.

As mentioned above, KOA patients have asymmetric foot posture and abnormal gait. However, whether there is a correlation between foot posture asymmetry and abnormal gait in patients with KOA, and whether there are differences in these indicators between unilateral and bilateral KOA patients, are still interesting topics worth exploring. Additionally, the limited number of relevant studies and the conflicting outcomes requires further investigation. The purpose of this study was to observe the characteristics of foot posture asymmetry and abnormal gait in patients with unilateral and bilateral KOA, and to explore the association between foot posture asymmetry, abnormal gait and the clinical symptoms and severity of KOA, so as to provide more comprehensive and scientific basis for the clinical diagnosis and rehabilitation intervention of KOA. The main hypothesis of this study was that patients with unilateral KOA would have more severe foot posture asymmetry and abnormal gait compared with patients with bilateral KOA. It was also expected that foot posture asymmetry, gait and plantar pressure parameters and symmetry indices would be closely related to clinical symptoms and disease severity.

Methods

Study design

This cross-sectional study was performed in the department of orthopedics of Guangdong Second Traditional Chinese Medicine Hospital from September 2021 to October 2022. The study protocol was approved by the Ethics Committee of Guangdong Second Traditional Chinese Medicine Hospital (No. 2021(K58)) and registered in Chinese Clinical Trial Registry (Registration No. ChiCTR2100050269). All experiments were performed in accordance with the relevant guidelines and regulations. Written informed consent was obtained from the individual (s) for the publication of any potentially identifiable images and for participation.

Participants

The sample size was calculated using PASS 15.0.5. To evaluate the difference in the percentage of FPI asymmetry score, when power = 0.8/0.85, the sample size should not be less than 50 (25/25)/58 (29/29). For the difference in the continuous variable, the sample size should be larger than 46 (power = 0.9, 23/23) for non-paired data or 56 (power = 0.85, 28/28) for paired data[18,19,36]. The inclusion criteria were: (I) age ≥ 50 years[37,38]; (II) met the diagnostic criteria of the American College of Rheumatology[39]; (III) Kellgren/Lawrence[40] (K/L) grade ≥ 1; (IV) BMI ≤ 30 kg/m^2; (V) had symptoms in the unilateral or bilateral knee joints; (VI) presence of predominantly medial compartment KOA; (VII) being able to walk independently without any assistive devices. The exclusion criteria were: (I) presence of other inflammatory rheumatic diseases affecting the lower extremities such as rheumatoid arthritis; (II) had concomitant neurologic diseases, severe cardiovascular and respiratory diseases or other musculoskeletal diseases; (III) had a history of trauma or surgery resulting in structural deformity of the foot; (IV) any vigorous exercise within 24 h before the test.

In this study, a total of 60 patients with KOA were enrolled in this study, and 30 patients with unilateral KOA and 30 patients with bilateral KOA were divided into the unilateral group (UG) and the bilateral group (BG), respectively. According to the symptom severity assessed by visual analogue scale (VAS) at activity, the symptomatic leg (the leg with the most severe symptoms when both sides are involved) is defined as the relatively severe leg (RSL) and the contralateral leg is defined as the relatively moderate leg (RML). Additionally, if patients with bilateral KOA have the same symptoms of leg pain, RSL and RML are defined by random methods (e.g., coin tossing).

We collected the demographic and clinical information of all patients, including age, gender, height, weight, and duration of disease, etc. The radiographs were scored according to K/L grading of radiographic disease severity[40]. The clinical symptoms were assessed by VAS at activity and Western Ontario and McMaster University Osteoarthritis Index (WOMAC)[41].

Assessment of foot posture

The FPI-6[42] was used to evaluate the foot posture on both feet. Our previous study[43] observed substantial inter-rater and test-retest reliability of FPI total score using the Weighted Kappa (Kw) coefficient (Kw = 0.66 and 0.72, respectively). According to the FPI total score, the feet were classified as three types: neutral (from 0 to 5), pronated (greater than or equal to 6), and supinated (less than or equal to − 1). Based on the previous research method[43], all participants were required to stand up, take a few steps forward, and then stand still, with their arms on their sides and looking forward, to avoid changes in foot posture caused by rotation.

Assessment of foot posture asymmetry

Foot posture asymmetry was assessed with the asymmetry score (difference in FPI total score between the two feet) according to the previous method[36], which was calculated as the FPI total score of the right foot minus the FPI total score of the left foot. Asymmetry score ranging from − 2 to + 2 represented normal, − 4 ≤ asymmetry score < − 2 or + 2 < asymmetry score ≤ + 4 was asymmetry, and severe asymmetry was < − 4 or > 4.

Measurement of gait and plantar pressure

The DIERS pedogait (DIERS International GmbH, Schlangenbad, German, Model: formetric) (Supplementary Fig. **S1**) was used to measure the gait and plantar pressure. This measurement system and the same series of systems have been verified in many studies[44–46]. The operation method is as follows: (I) Preparation: ask the participants to walk on the DIERS pedogait treadmill at a uniform speed and slowly for about 10 min in a state of barefoot and natural relaxation, so as to make the body active and gradually adapt to the speed of the treadmill; (II) Test: after the participants gradually stabilize the walking state, the displayed speed is the target speed, telling the participants to look ahead visually, do not touch the handrail, do not step, and then collect data for 30 s under the target speed state for a total of three times, and take the average as the final result, in order to improve the reliability of the results. In this study, the process starting from the right heel touching the ground to the second right heel touching the ground was defined as a gait cycle. The instrument divided the sole of the foot into 10 separate areas including: Hallux, Toe II to V, Metatarsal I, Metatarsal II, Metatarsal III, Metatarsal IV, Metatarsal V, Midfoot, Heel Lateral, Heel Medial. The pressure in each area was represented by a different colored curve (Supplementary Fig. **S2**).

The following test indexes were collected: (1) Gait spatiotemporal parameters: (I) Temporal parameters: single support phase (%), double support phase (%), standing phase (%), swing phase (%), stride time (ms), and step time (ms); (II) Spatial parameters: step speed (km/h), step length (cm), stride length (cm), and stride width (cm). (2) Plantar pressure parameters: peak pressure (kPa) of hallux, toe 2 to 5, 1st, 2nd, 3rd, 4th and 5th metatarsal, midfoot, lateral heel, and medial heel.

Assessment of gait and plantar pressure symmetry index

Inter-limb comparison of gait and plantar pressure variables was evaluated using a symmetry index (SI) modified from one defined by previous studies[47,48]:

$$SI = \frac{|X_L - X_R|}{1/2\,(X_L + X_R)} \times\ 100\%$$

Where X_L is a gait and plantar pressure variable recorded for the left leg and X_R is the corresponding variable for the right leg. SI = 0 indicates perfect symmetry. A SI ≤ 10% or less than a 10% difference between sides indicates acceptable asymmetry[47,48]. This modified equation determines asymmetry independent of side. The absolute value function determines the magnitude of asymmetry regardless of the relationship between the RSL and RML.

Statistical analysis

All statistical tests were performed using SPSS 26.0 software (IBM, Corp., NY, United States). The normality was assessed firstly on collected data using the Shapiro-Wilks test. Quantitative variables that conformed to normal distribution were presented as mean and standard deviation (SD), while those that did not conform were presented as median and interquartile range (IQR), and qualitative variables as counts and percentages. Paired Student's t-test (normal distribution) or Wilcoxon signed-rank test (non-normal distribution) were used to determine the differences between the two lower limbs. The differences between two groups were compared by independent samples t-test (normal distribution) or Mann-Whitney U test (non-normal distribution). Chi-square tests were used to compare the categorical variables between the two groups. When performing correlation analyses, data from patients with unilateral and bilateral KOA were merged. Pearson correlation test (normal distribution) or Spearman correlation test (non-normal distribution) were used to examine the relationships between foot posture asymmetry, gait symmetry index, symptom-related scores, and K-L grade.

The influencing factors of foot posture asymmetry were analyzed by ordinal multinomial logistic regression analysis. Statistical significance was defined as $p < 0.05$.

Results

Participant characteristics

A total of 60 participants with KOA were included in this study. Descriptive statistics of all participants were summarized in Table 1. No significant differences were observed in age, gender, height, weight, body mass index (BMI), duration of disease, frequency of RSL, K/L grade, symptom-related scores (including VAS and WOMAC score), and FPI score between two groups.

Foot posture asymmetry analysis

As shown in Fig. 1, the asymmetry score, that is, the difference in FPI score between the two feet, was mainly concentrated between −3 and 3 in BG, while it was relatively widely distributed in UG. According to the asymmetry score, the foot posture asymmetry of the two groups of patients was divided into three types: normal, asymmetry and severe asymmetry. The results indicated that there was a significant difference in the asymmetry score between the two groups ($p = 0.036$). The proportion of participants classified as normal in BG (66.67%) was higher than that in UG (40.00%), and the overall percentage of asymmetry and severe asymmetry were lower in BG (33.33%) than in UG (60.00%), $p = 0.040$, as shown in Table 2.

Gait and plantar pressure analysis

When comparing RSL with RML within the group, the results demonstrated that there were no significant differences in any gait spatiotemporal and plantar pressure parameters. When comparing between groups, no significant differences were also observed in any gait spatiotemporal and plantar pressure parameters of RSL. Additionally, the comparison of symmetry indices between groups also revealed no significant differences. SI values above the 0–10% range were common and similar between UG and BG, suggesting that substantial asymmetry on many indicators within the two groups (Supplementary Table **S1**).

Correlation analysis between foot posture asymmetry, gait and plantar pressure parameters and symmetry indices, symptom-related scores, and K-L grade

Spearman correlation analysis indicated that there was a positive relationship between foot posture asymmetry and VAS score, WOMAC pain score, and K/L grade ($p = 0.002$, 0.017, and 0.000, respectively). The results were detailed in Table 3. Moreover, there was a negative correlation between walking velocity and foot posture asymmetry, VAS score, the three sub-scores and the total score of WOAMC, and K-L grade ($p = 0.018$, 0.000,

Variable	UG ($n = 30$)	BG ($n = 30$)	p	Merged
Age (years)	63.63 ± 1.03	65.87 ± 1.40	0.245	64.75 ± 0.87
Gender (male/female)	8/22	5/25	0.347	13/60
Height (cm)	156.50 (155.00, 162.00)	156.00 (154.00, 160.50)	0.357	156.00 (155.00, 162.00)
Weight (kg)	62.17 ± 1.23	63.62 ± 1.34	0.427	62.89 ± 0.91
BMI (kg/m^2)	24.57 ± 0.41	25.51 ± 0.46	0.134	25.04 ± 0.31
Duration of disease (years)	3.50 (0.88, 5.25)	2.50 (0.48, 6.00)	0.528	3.00 (0.50, 6.00)
RSL (left/right)	13/17	14/16	0.795	27/43
K/L grade (RSL)			0.787	
I	3	1		4
II	6	10		16
III	19	17		36
IV	2	2		4
VAS (RSL)	6.00 (5.00, 7.00)	6.00 (5.75, 7.00)	0.216	6.00 (6.00, 7.00)
WOMAC score				
Pain	7.17 ± 0.49	7.50 ± 0.48	0.631	7.33 ± 0.34
Stiffness	2.40 ± 0.26	2.43 ± 0.23	0.924	2.42 ± 0.17
Physical function	25.20 ± 1.25	26.40 ± 1.35	0.516	25.80 ± 0.91
Total	34.77 ± 1.86	36.33 ± 1.76	0.543	35.55 ± 1.27
FPI score				
RSL	6.00 (1.50, 7.25)	6.00 (− 1.00, 7.00)	0.893	6.00 (− 0.75, 7.00)
RML	3.50 (− 1.25, 7.25)	4.00 (− 1.00, 6.00)	0.941	4.00 (− 1.00, 6.00)
FPI asymmetry score	1.20 ± 0.58	0.33 ± 0.45	0.243	0.77 ± 0.37

Table 1. Demographics, symptom-related scores, and foot posture of the study participants. BG, bilateral group; BMI, body mass index; FPI, Foot Posture Index; K/L, Kellgren/Lawrence; RML, relatively moderate leg; RSL, relatively severe leg; UG, unilateral group; VAS, visual analogue scale; WOMAC, western Ontario McMasters universities osteoarthritis Index.

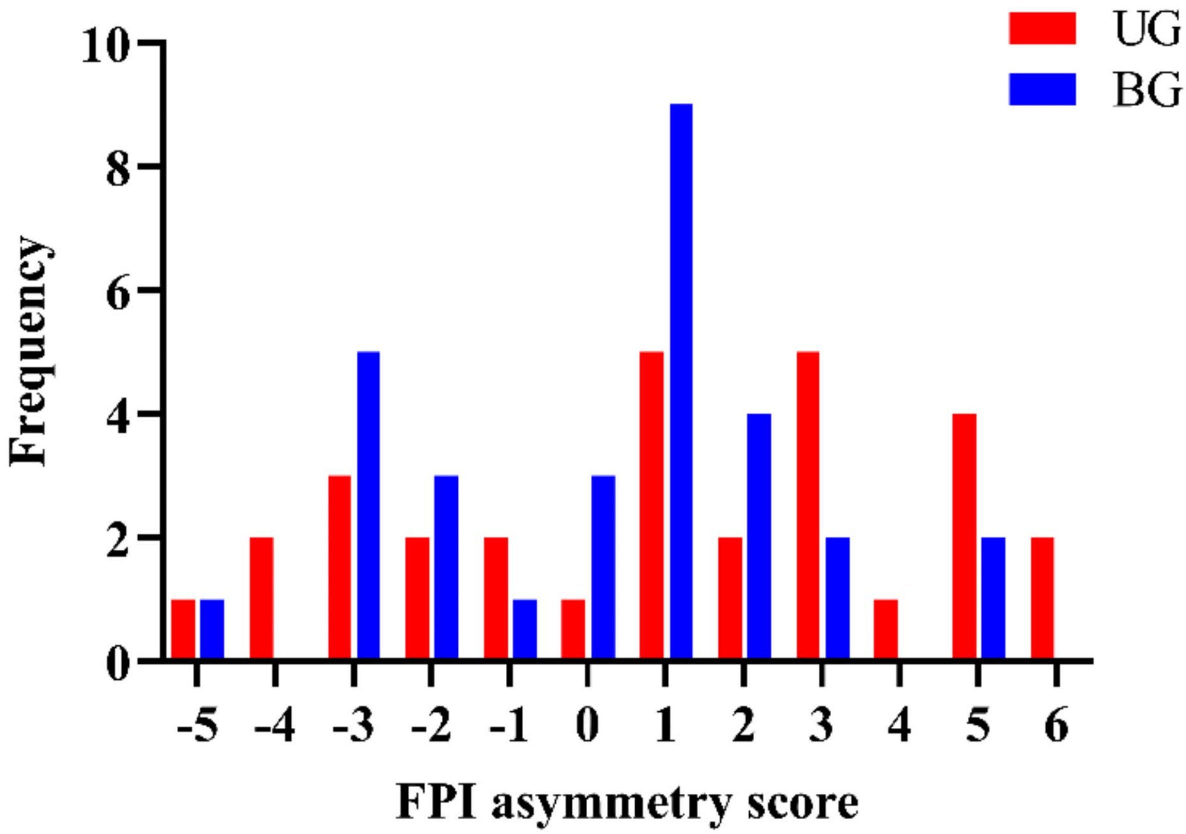

Fig. 1. The FPI asymmetry score of two groups. BG, bilateral group; FPI, Foot Posture Index; UG, unilateral group.

		FPI asymmetry score		
	Normal	Asymmetry	Severe asymmetry	*p*
UG	12 (40.00%)	11 (36.67%)	7 (23.33%)	0.036*
BG	20 (66.67%)	7 (23.33%)	3 (10.00%)	

Table 2. Comparison of FPI asymmetry score between two groups ($n = 30$). BG, bilateral group; FPI, Foot Posture Index; UG, unilateral group. *$p < 0.05$.

	VAS	WOMAC (pain)	WOMAC (stiffness)	WOMAC (physical function)	WOMAC-total	K-L grade
r	0.385	0.308	0.154	0.202	0.235	0.583
p	0.002*	0.017*	0.240	0.121	0.070	0.000*

Table 3. Correlation between foot posture asymmetry and symptom-related scores and K-L grade. K/L, Kellgren/Lawrence; VAS, visual analogue scale; WOMAC, western Ontario McMasters universities osteoarthritis Index. *$p < 0.05$.

0.000, 0.004, 0.000, 0.000, and 0.000, respectively). The stride time, SI of peak pressure of 5th metatarsal and midfoot were negatively related to foot posture asymmetry ($p = 0.046$, 0.007, and 0.024, respectively). The double support phase was positively correlated with the VAS score, WOMAC total score, and K-L grade ($p = 0.010$, 0.032, and 0.007, respectively). The SI of step length was negatively associated with the VAS score ($p = 0.028$). The SI of peak pressure of 1st metatarsal was also positively related to WOMAC stiffness score ($p = 0.003$). There was a significant positive association between the SI of peak pressure of lateral heel and K-L grade ($p = 0.002$). The detailed results were presented in Table 4.

	Foot posture asymmetry		VAS		WOMAC (pain)		WOMAC (stiffness)		WOMAC (physical function)		WOMAC (total)		K-L grade	
	r	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*
Step speed (km/h)	− 0.304	0.018*	− 0.860	0.000*	− 0.628	0.000*	− 0.369	0.004*	− 0.641	0.000*	− 0.687	0.000*	− 0.304	0.018*
Stride length (cm)	− 0.199	0.127	0.077	0.557	0.037	0.779	0.032	0.796	0.108	0.412	0.092	0.485	− 0.137	0.297
Stride width (cm)	0.051	0.701	0.158	0.228	− 0.065	0.619	0.154	0.241	0.097	0.460	0.087	0.509	0.105	0.426
Stride time (ms)	− 0.259	0.046*	− 0.025	0.850	− 0.114	0.386	0.004	0.977	− 0.021	0.875	− 0.045	0.733	− 0.149	0.257
Double support phase (%)	0.182	0.165	0.332	0.010*	0.242	0.062	0.172	0.188	0.249	0.055	0.277	0.032*	0.342	0.007*
SI (step length) (%)	0.021	0.876	− 0.284	0.028*	− 0.036	0.783	− 0.036	0.787	− 0.022	0.870	− 0.042	0.751	− 0.167	0.202
SI (step time) (%)	0.088	0.502	− 0.053	0.689	− 0.124	0.344	− 0.004	0.975	− 0.132	0.313	− 0.131	0.320	0.015	0.907
SI (standing phase) (%)	− 0.089	0.499	0.094	0.475	0.012	0.925	0.008	0.951	0.022	0.867	0.011	0.931	− 0.101	0.442
SI (swing phase) (%)	− 0.250	0.054	− 0.079	0.546	0.026	0.841	− 0.105	0.425	− 0.011	0.932	− 0.028	0831	− 0.152	0.246
SI (single support phase) (%)	− 0.019	0.885	− 0.009	0.945	0.086	0.512	− 0.035	0.788	0.035	0.789	− 0.035	0.788	− 0.225	0.084
SI (peak plantar pressure) (%)														
Hallux	0.138	0.292	0.132	0.316	− 0.003	0.982	0.142	0.279	0.049	0.708	0.064	0.625	0.025	0.849
Toe 2 to 5	− 0.002	0.991	− 0.118	0.368	− 0.199	0.128	− 0.241	0.064	− 0.099	0.452	− 0.163	0.212	0.072	0.582
1st Metatarsal	0.184	0.159	0.166	0.204	0.247	0.057	0.379	0.003*	0.154	0.242	0.233	0.073	0054	0.682
2nd Metatarsal	− 0.097	0.459	− 0.055	0.678	− 0.016	0.901	− 0.150	0.252	− 0.041	0.758	− 0.039	0.767	− 0.096	0.465
3rd Metatarsal	0.066	0.618	− 0.064	0.628	0.075	0.571	− 0.195	0.136	− 0.052	0.691	− 0.035	0.792	0.057	0.663
4th Metatarsal	− 0.106	0.419	− 0.058	0.658	0.049	0.709	− 0.008	0.954	− 0.095	0.469	− 0.055	0.676	0.029	0.827
5th Metatarsal	− 0.346	0.007*	− 0.087	0.507	− 0.232	0.074	− 0.092	0.483	− 0.147	0.262	− 0.161	0.218	− 0.126	0.336
Midfoot	− 0.292	0.024*	− 0.076	0.563	0.014	0.915	− 0.172	0.189	− 0.016	0.903	− 0.026	0.845	− 0.248	0.056
Lateral heel	0.214	0.101	0.083	0.529	− 0.042	0.752	− 0.167	0.201	− 0.069	0.600	− 0.083	0.527	0.401	0.002*
Medial heel	− 0.044	0.739	− 0.141	0.281	− 0.013	0.922	− 0.030	0.818	− 0.181	0.167	− 0.140	0.287	− 0.127	0.335

Table 4. Correlation between gait and plantar pressure parameters and symmetry indices and foot posture asymmetry, symptom-related scores, and K-L grade. K/L, Kellgren/Lawrence; SI, symmetry index; VAS, visual analogue scale; WOMAC, western Ontario McMasters universities osteoarthritis Index. $^{*}p < 0.05$.

Ordinal multinomial logistic regression

Ordinal multivariate logistic regression was used to analyze the independent influencing factors of foot posture asymmetry. The foot posture asymmetry was set as the dependent variable, and setting the VAS score, WOMAC pain score, step speed, stride time, SI of peak pressure of 5th Metatarsal and midfoot as covariates, and K-L grade as a factor, the results indicated that the SI of peak pressure of midfoot and K-L grade (I, II and III) were independent influencing factors of the foot posture asymmetry (β = -0.075, -21.923,-25.300,-22.024, respectively, $p < 0.05$).

Discussion

The purpose of this study was to observe the characteristics of foot posture asymmetry and abnormal gait in patients with unilateral and bilateral KOA, and to explore the association between foot posture asymmetry, abnormal gait and the clinical symptoms and severity of KOA. Our results indicated that the overall proportion of asymmetry and severe asymmetry in foot posture were higher in UG than in BG. Although both groups showed considerable asymmetry on various gait parameters, there were no significant differences between the two groups. Furthermore, foot posture asymmetry, multiple gait and plantar pressure parameters and symmetry indices were closely related to clinical symptoms and disease severity. There results were largely consistent with our hypothesis.

KOA is a chronic, disabling musculoskeletal disease that affects the elderly and could cause joint pain, swelling, stiffness, and dysfunction, severely affecting quality of life[49]. It is well established that the foot posture and gait of patients with KOA differ from those of healthy individuals[16,24–27].

Since KOA can affect one or both knees, there are clinically relevant and study design questions that are based on whether foot posture, gait and plantar pressure changes as a function of the number of diseased knees. Since most patients with unilateral KOA have bilateral disease, should both knees be treated clinically? Moreover, for KOA researchers involved in studies in which foot posture asymmetry, gait and plantar pressure parameters and symmetry indices are outcome measures, is it appropriate to treat patients with unilateral and bilateral KOA as a single cohort[48]? Therefore, understanding whether there is a correlation between foot posture asymmetry and abnormal gait in patients with KOA, and whether there are differences in foot posture asymmetry and gait between patients with unilateral or bilateral KOA, is essential for planning research and rehabilitation treatment involving KOA.

One would intuitively presume that patients with unilateral KOA would rely on the unaffected leg when performing activities or functional tasks and would show better functional performance than patients with bilateral KOA[29]. Our results indicated that patients with unilateral and bilateral KOA showed clinical similarities in terms of pain intensity and functional ability, which did not support this hypothesis. Several previous studies[48,50] have also showed similar results. However, two other studies[51,52] reported higher pain levels and worse physical function in patients with bilateral KOA. This may be due to the significant difference in BMI between the two groups of patients in the two studies. Previous studies[53,54] have shown that BMI is significantly positively correlated with self-reported physical function scores and disease severity in KOA patients.

Poor joint biomechanics is one of the high-risk factors for KOA[55]. Given the important role of the foot in receiving and distributing forces during walking, the characteristics and mechanics of the foot, including static foot posture and dynamic foot function, may have a significant impact on the musculoskeletal condition of the lower limbs[56]. From a biomechanical perspective, as movement shifts proximally, the degree of movement of the foot, subtalar and ankle joints affect the alignment of the lower limbs[10]. Excessive varus/valgus of the subtalar joint may increase external/internal rotation of the tibia, which in turn is assumed to undermine the normal mechanics of the tibiofemoral joint[57]. These axial connections between the subtalar and tibiofemoral joints suggest that the kinematics of the foot and ankle may have an impact on lateral rotation and frontal measurements of the knee joint[10]. Therefore, the foot is thought to play an important role in KOA[58]. There is evidence that changes in foot posture in KOA patients may lead to biomechanical imbalance of the lower limbs, resulting in inter-limb asymmetry, thereby aggravating KOA[19]. A previous study[18] has reported that the proportion of asymmetric foot posture in patients with KOA is higher than that in healthy subjects. In this study, according to the asymmetry of foot posture, we divided them into normal, asymmetry and severe asymmetry. The results indicated that the normal proportion of patients with bilateral KOA was higher than that of patients with unilateral KOA, and a more asymmetric foot posture was closely associated with higher VAS score, WOMAC pain score, WOMAC total score, and K-L grade, which is partially consistent with the results reported in a previous study[19]. There is evidence that for KOA patients, the presence of unilateral pain is related to the asymmetry of knee biomechanics[30], and foot posture is closely associated with knee biomechanics[59]. Therefore, the proportion of asymmetry and severe asymmetry in foot posture in KOA patients with unilateral pain is higher than that in KOA patients with bilateral pain. From the perspective of foot posture asymmetry, it seems inappropriate to include patients with unilateral and bilateral KOA as a single cohort in clinical studies.

Numerous previous studies have investigated the gait spatiotemporal and plantar pressure parameters of KOA patients. However, most studies only focus on unilateral KOA patients or bilateral KOA patients, and few studies have compared the differences in gait spatiotemporal and plantar pressure parameters between unilateral and bilateral KOA patients. Messier et al.[48] noted that the comparisons of walking speed, stride length, support time, initial double support and their corresponding symmetry indices between UG and BG presented no significant differences. Creaby et al.[30] also observed similar walking speed in UG and BG. These are generally consistent with our results, which showed that there were no significant differences in any gait spatiotemporal and plantar pressure variables, whether comparing RSL with RML within groups, RSL or SI between groups. Hence, unilateral and bilateral KOA patients matched for baseline data have statistically similar gait and plantar pressure characteristics. For non-significant results, they may be interpreted as a Type 2 statistical error resulting from small sample size or relatively low statistical power. From the perspective of gait and plantar pressure parameters and symmetry indices, the two subsets of patients with unilateral and bilateral KOA can be considered as a single cohort.

To the best of our knowledge, the clinically relevant threshold for symmetrical gait is unclear and there is no gold standard for what is considered symmetrical gait. Previous studies[48,60] have suggested that a 10% difference between the two lower extremities is acceptable based on differences in performance and strength variables. Using this definition of symmetry, there is evidence that asymmetric gait is highly prevalent in both healthy individuals and patients with KOA. Lathrop-Lambach et al.[60] investigated bilateral gait data from 182 healthy, pain-free subjects and showed that there is a large amount of asymmetry between the limbs in healthy people. Similarly, Herzog et al.[47] found that the upper and lower limits of the SI values were unexpectedly large, so that they concluded that the gait of healthy people is asymmetric. In our study, the gait spatiotemporal and plantar pressure data were symmetrical in the UG and BG, but the peak plantar pressure in each region presented relatively large asymmetries. Taken together, these studies demonstrated that striving to correct "abnormal gait" caused by KOA or other neuromuscular or musculoskeletal diseases by making the gait more symmetrical may not be appropriate in many cases.

There is evidence that unilateral KOA can affect the contralateral knee over time, leading to bilateral involvement. Therefore, it is recommended that in the management of unilateral KOA, even if only one knee is symptomatic, both knees should be treated simultaneously[30]. This recommendation seems logical. Spector et al.[61] showed that more than one-third of patients with unilateral KOA will develop bilateral KOA within 2 years. In another long-term prospective cohort study[31], the data demonstrated that 80% of patients with unilateral KOA will develop bilateral knee disease within 12 years. Our results showed no differences in gait spatiotemporal and plantar pressure variables and symmetry indices, which also supported this recommendation. Additionally, it should be noted that cross-sectional analyses can hardly explain the response of a group to a longitudinal intervention.

Several studies have shown that abnormal foot posture can significantly alter the biomechanics of the entire lower limb[59], leading to compensatory changes in gait, including spatiotemporal and plantar pressure parameters[32,62,63]. Specifically, abnormal foot posture, such as excessive pronation or supination, alters the mechanical load distribution at the knee and hip joints[15,64], causing these joints to experience different stresses during the gait cycle, thereby inducing compensatory actions. On the contrary, this compensatory gait can further increase stresses in specific areas of the foot and may exacerbate pre-existing foot posture abnormalities. However, clinical evidence on the correlation of foot posture with gait spatiotemporal and plantar pressure parameters in patients with KOA is still lacking. Therefore, our study also investigated whether there is a correlation between foot posture asymmetry and gait spatiotemporal and plantar pressure parameters and symmetry indices in patients with KOA. The results showed that foot posture asymmetry was closely related to the step speed, stride time, and SI of peak pressure of 5th metatarsal and midfoot (Table 4). Moreover, we also explored the correlation between gait and plantar pressure parameters and symmetry indices with symptom-related scores and K-L grade. The results indicated that the walking velocity, double support phase, SI of step length, and SI of peak pressure of 1st metatarsal, and lateral heel were closely correlated with the symptom-related scores and K-L grade (Table 4). Li et al.[65] showed that the walking velocity, single support phase and double support phase were correlated with the three sub-scores and the total score of WOAMC, and step length, stride length and step time were correlated with WOMAC physical function score and total score. This is partially consistent with our results, possibly because the former only included patients with bilateral KOA, and step length, step time, and single-stance phase were all expressed in the form of ratio (left lower limb: right lower limb), which was unclear in correlation with the SI used in our study. He et al.[21] also reported that in unilateral KOA patients, the severity of KOA (K-L grade) was correlated with the peak pressure of the hallux, toe 2 to 5, 5th metatarsal, midfoot, lateral heel, and medial heel on the affected side and the peak pressure of the 2nd, 3rd, and 4th metatarsal on the unaffected side. Since the SI was not calculated in the above study, this limits comparison with our results. Although this study was not designed to identify potential assessment indicators of KOA, it raises the possibility that foot posture asymmetry, gait and plantar pressure parameters and symmetry indices may serve as assessment indicators and ultimately as outcome measures.

Peak plantar pressure (PPP) is the most commonly used plantar pressure variable to express foot loading. This value represents the maximum load on the plantar area during one step[66]. Another variable that is increasingly used to assess plantar load is the pressure-time integral (PTI). This variable describes the cumulative effect of pressure in an area of the foot over time, providing a value for the total load exposure in the plantar area during one step[67]. In this study, we only selected the PPP as an indicator for the following reasons: First, a study on plantar pressure showed that there was a high degree of interdependence and consistency between PPP and PTI, and the value of reporting both variables may be limited[68]. Moreover, a more practical reason for choosing PPP instead of PTI is that PPP is more comprehensible and can be directly interpreted on the screen during measurement[68].

There are some limitations in the present study. Firstly, the sample size of this study was relatively small, and it is important to further validate our findings in a larger cohort of participants. Secondly, this study was cross-sectional in design, and we could not determine the causal relationship between abnormality in foot posture and gait and the development of unilateral or bilateral KOA. Further longitudinal studies are needed to establish the role of foot posture asymmetry and gait asymmetry in disease development and progression. Thirdly, due to the lack of a matched healthy control group assessed comparatively with KOA patients, the associations of foot posture asymmetry with gait and plantar pressure parameters and symmetry indices in healthy subjects are unclear, and this study could not determine differences in associations between KOA patients and healthy subjects. Fourthly, this study failed to include other factors that may affect foot posture and gait, such as lower limb muscle strength and joint mobility, which should be supplemented in future studies. Fifthly, since medial compartment KOA is more common, we included subjects with predominantly medial compartment KOA, which may have led to some bias. Additionally, future studies should combine multidisciplinary methods such as biomechanics, imaging, and molecular biology to further explore the specific mechanisms of abnormal foot posture and gait in the onset and progression of KOA. Through these studies, it is expected to develop more effective early diagnosis and intervention methods, and ultimately improve the quality of life of patients with KOA.

Conclusion

Our study indicated that both unilateral and bilateral KOA patients have foot posture asymmetry and gait asymmetry, but the foot posture asymmetry of the former is more severe than that of the latter. Intervention for this population should treat simultaneously both knee joints. The evaluation and monitoring of foot posture asymmetry, gait and plantar pressure parameters and symmetry indices can provide a more comprehensive and scientific basis for the prevention and treatment of KOA.

Data availability

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

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References

1. Davis, A. M. Osteoarthritis year in review: rehabilitation and outcomes. *Osteoarthr. Cartil.* **20** (3), 201–206 (2012).
2. Zhang, W. et al. OARSI recommendations for the management of hip and knee osteoarthritis: part III: changes in evidence following systematic cumulative update of research published through January 2009. *Osteoarthr. Cartil.* **18** (4), 476–499 (2010).
3. Michael, J. W., Schlüter-Brust, K. U. & Eysel, P. The epidemiology, etiology, diagnosis, and treatment of osteoarthritis of the knee. *Dtsch. Arztebl Int.* **107** (9), 152–162 (2010).
4. Sánchez Romero, E. A. et al. Is a combination of Exercise and Dry needling effective for knee OA? *Pain Med. (Malden Mass)*. **21** (2), 349–363 (2020).
5. Sanchez-Romero, A. et al. Efficacy of manual therapy on facilitatory nociception and endogenous pain modulation in older adults with knee osteoarthritis: a case series. *Applied Sciences*. 11(4):1895 (2021).
6. Reichenbach, S. et al. Effect of biomechanical footwear on knee Pain in people with knee osteoarthritis: the BIOTOK Randomized Clinical Trial. *Jama*. **323** (18), 1802–1812 (2020).
7. Cui, A. et al. Global, regional prevalence, incidence and risk factors of knee osteoarthritis in population-based studies. *EClinicalMedicine*. **29–30**, 100587 (2020).
8. Blagojevic, M., Jinks, C., Jeffery, A. & Jordan, K. P. Risk factors for onset of osteoarthritis of the knee in older adults: a systematic review and meta-analysis. *Osteoarthr. Cartil.* **18** (1), 24–33 (2010).
9. Elbaz, A. et al. Association between knee osteoarthritis and functional changes in Ankle Joint and Achilles Tendon. *J. Foot Ankle Surg.* **56** (2), 238–241 (2017).
10. Gates, L. S., Bowen, C. J., Sanchez-Santos, M. T., Delmestri, A. & Arden, N. K. Do foot & ankle assessments assist the explanation of 1 year knee arthroplasty outcomes? *Osteoarthr. Cartil.* **25** (6), 892–898 (2017).
11. Redmond, A. C., Crane, Y. Z. & Menz, H. B. normative values for the Foot posture index. *J. Foot Ankle Res.* **1** (1), 6 (2008).
12. Evans, A. M., Copper, A. W., Scharfbillig, R. W., Scutter, S. D. & Williams, M. T. Reliability of the foot posture index and traditional measures of foot position. *J. Am. Podiatr. Med. Assoc.* **93** (3), 203–213 (2003).
13. Gijon-Nogueron, G., Marchena-Rodriguez, A., Montes-Alguacil, J. & Evans, A. M. Evaluation of the paediatric foot using footprints and foot posture index: a cross-sectional study. *J. Paediatr. Child. Health*. **56** (2), 201–206 (2020).
14. Ohi, H. et al. Association of frontal plane knee alignment with foot posture in patients with medial knee osteoarthritis. *BMC Musculoskelet. Disord*. **18** (1), 246 (2017).
15. Al-Bayati, Z., Coskun Benlidayi, I. & Gokcen, N. Posture of the foot: don't keep it out of sight, out of mind in knee osteoarthritis. *Gait Posture*. **66**, 130–134 (2018).
16. Levinger, P. et al. Foot posture in people with medial compartment knee osteoarthritis. *J. Foot Ankle Res.* **3**, 29 (2010).
17. Riskowski, J. L., Hagedorn, T. J., Dufour, A. B. & Hannan, M. T. Functional foot symmetry and its relation to lower extremity physical performance in older adults: the Framingham Foot Study. *J. Biomech.* **45** (10), 1796–1802 (2012).
18. Chen, Z. et al. Association between Foot Posture Asymmetry and Static Stability in Patients with Knee Osteoarthritis: A Case-Control Study. *Biomed. Res. Int.* : 1890917 (2020). (2020).
19. Chen, Z. et al. Comparison of the asymmetries in Foot posture and Properties of gastrocnemius muscle and Achilles Tendon between patients with unilateral and bilateral knee osteoarthritis. *Front. Bioeng. Biotechnol.* **9**, 636571 (2021).
20. Elbaz, A. et al. Novel classification of knee osteoarthritis severity based on spatiotemporal gait analysis. *Osteoarthr. Cartil.* **22** (3), 457–463 (2014).
21. He, Y. J. et al. Static and dynamic Plantar pressure distribution in 94 patients with different stages of unilateral knee osteoarthritis using the Footscan platform system: an observational study. *Med. Sci. Monit.* **29**, e938485 (2023).
22. Sethi, D., Bharti, S. & Prakash, C. A comprehensive survey on gait analysis: history, parameters, approaches, pose estimation, and future work. *Artif. Intell. Med.* **129**, 102314 (2022).
23. Broström, E. W., Esbjörnsson, A. C., von Heideken, J. & Iversen, M. D. Gait deviations in individuals with inflammatory joint diseases and osteoarthritis and the usage of three-dimensional gait analysis. *Best Pract. Res. Clin. Rheumatol.* **26** (3), 409–422 (2012).
24. Peixoto, J. G. et al. Analysis of symmetry between lower limbs during gait of older women with bilateral knee osteoarthritis. *Aging Clin. Exp. Res.* **31** (1), 67–73 (2019).
25. Ismailidis, P. et al. Side to side kinematic gait differences within patients and spatiotemporal and kinematic gait differences between patients with severe knee osteoarthritis and controls measured with inertial sensors. *Gait Posture*. **84**, 24–30 (2021).
26. Panyarachun, P., Angthong, C., Jindasakchai, P., Rajbhandari, P. & Rungrattanawilai, N. Abnormal foot pressure in older adults with knee osteoarthritis: a systematic review. *Eur. Rev. Med. Pharmacol. Sci.* **26** (17), 6236–6241 (2022).
27. Zhang, Z., Wang, L., Hu, K. & Liu, Y. Characteristics of Plantar loads during walking in patients with knee osteoarthritis. *Med. Sci. Monit.* **23**, 5714–5719 (2017).
28. Taş, S. et al. Effects of severity of osteoarthritis on the temporospatial gait parameters in patients with knee osteoarthritis. *Acta Orthop. Traumatol. Turc.* **48** (6), 635–641 (2014).
29. Marmon, A. R., Zeni, J. A. Jr & Snyder-Mackler, L. Perception and presentation of function in patients with unilateral versus bilateral knee osteoarthritis. *Arthritis Care Res. (Hoboken)*. **65** (3), 406–413 (2013).

30. Creaby, M. W., Bennell, K. L. & Hunt, M. A. Gait differs between unilateral and bilateral knee osteoarthritis. *Arch. Phys. Med. Rehabil.* **93** (5), 822–827 (2012).
31. Metcalfe, A. J., Andersson, M. L., Goodfellow, R. & Thorstensson, C. A. Is knee osteoarthritis a symmetrical disease? Analysis of a 12 year prospective cohort study. *BMC Musculoskelet. Disord*. **13**, 153 (2012).
32. Requelo-Rodríguez, I. et al. Assessment of selected spatio-temporal gait parameters on subjects with pronated Foot posture on the basis of measurements using OptoGait. A case-control study. *Sens. (Basel)* **21**(8), 2805 (2021).
33. Fernández-Seguín, L. M. et al. Comparison of plantar pressures and contact area between normal and cavus foot. *Gait Posture*. **39** (2), 789–792 (2014).
34. Burns, J., Crosbie, J., Hunt, A. & Ouvrier, R. The effect of pes cavus on foot pain and plantar pressure. *Clin. Biomech. (Bristol Avon)*. **20** (9), 877–882 (2005).
35. McKay, M. J. et al. Spatiotemporal and plantar pressure patterns of 1000 healthy individuals aged 3-101 years. *Gait Posture*. **58**, 78–87 (2017).
36. Rokkedal-Lausch, T., Lykke, M., Hansen, M. S. & Nielsen, R. O. normative values for the foot posture index between right and left foot: a descriptive study. *Gait Posture*. **38** (4), 843–846 (2013).
37. Hochberg, M. C. et al. Guidelines for the medical management of osteoarthritis. Part II. Osteoarthritis of the knee. American College of Rheumatology. *Arthritis Rheum.* **38** (11), 1541–1546 (1995).
38. Allen, K. D., Thoma, L. M. & Golightly, Y. M. Epidemiology of osteoarthritis. *Osteoarthr. Cartil.* **30** (2), 184–195 (2022).
39. Altman, R. et al. Development of criteria for the classification and reporting of osteoarthritis. Classification of osteoarthritis of the knee. Diagnostic and Therapeutic Criteria Committee of the American Rheumatism Association. *Arthritis Rheum.* **29** (8), 1039–1049 (1986).
40. KELLGREN, J. H. & LAWRENCE, J. S. Radiological assessment of osteo-arthrosis. *Ann. Rheum. Dis.* **16** (4), 494–502 (1957).
41. Ackerman, I. Western Ontario and McMaster universities osteoarthritis Index (WOMAC). *Aust J. Physiother*. **55** (3), 213 (2009).
42. Huang, C., Chen, L. Y., Liao, Y. H., Masodsai, K. & Lin, Y. Y. Effects of the Short-Foot Exercise on Foot Alignment and muscle hypertrophy in Flatfoot individuals: a Meta-analysis. *Int. J. Environ. Res. Public. Health* **19**(19), 11941 (2022).
43. Wang, Y. et al. Reliability of foot posture index (FPI-6) for evaluating foot posture in patients with knee osteoarthritis. *Front. Bioeng. Biotechnol.* **11**, 1103644 (2023).
44. Żurawski, A. et al. Effect of thoracic kyphosis and lumbar lordosis on the distribution of ground reaction forces on the feet. *Orthop. Res. Rev.* **14**, 187–197 (2022).
45. Song, J. et al. Differential diagnosis between Parkinson's disease and atypical parkinsonism based on gait and postural instability: Artificial intelligence using an enhanced weight voting ensemble model. *Parkinsonism Relat. Disord*. **98**, 32–37 (2022).
46. Yang, D. J. et al. Effect of changes in postural alignment on foot pressure and walking ability of stroke patients. *J. Phys. Ther. Sci.* **27** (9), 2943–2945 (2015).
47. Herzog, W., Nigg, B. M., Read, L. J. & Olsson, E. Asymmetries in ground reaction force patterns in normal human gait. *Med. Sci. Sports Exerc.* **21** (1), 110–114 (1989).
48. Messier, S. P., Beavers, D. P., Herman, C., Hunter, D. J. & DeVita, P. Are unilateral and bilateral knee osteoarthritis patients unique subsets of knee osteoarthritis? A biomechanical perspective. *Osteoarthr. Cartil.* **24** (5), 807–813 (2016).
49. Whittaker, J. L., Truong, L. K., Dhiman, K. & Beck, C. Osteoarthritis year in review 2020: rehabilitation and outcomes. *Osteoarthr. Cartil.* **29** (2), 190–207 (2021).
50. Chen, W. et al. Comparison of the asymmetries in muscle mass, biomechanical property and muscle activation asymmetry of quadriceps femoris between patients with unilateral and bilateral knee osteoarthritis. *Front. Physiol.* **14**, 1126116 (2023).
51. Oliveira, L. A. S. et al. Comparison between pain intensity, functionality, central sensitization, and self-efficacy in individuals with unilateral or bilateral knee osteoarthritis: a cross-sectional study. *Rev. Assoc. Med. Bras. ()*. 68(8): 1048-52 (2022). (1992).
52. Petrella, M. et al. Kinetics, kinematics, and knee muscle activation during sit to stand transition in unilateral and bilateral knee osteoarthritis. *Gait Posture*. **86**, 38–44 (2021).
53. Sharma, L., Lou, C., Cahue, S. & Dunlop, D. D. The mechanism of the effect of obesity in knee osteoarthritis: the mediating role of malalignment. *Arthritis Rheum.* **43** (3), 568–575 (2000).
54. Creamer, P., Lethbridge-Cejku, M. & Hochberg, M. C. Factors associated with functional impairment in symptomatic knee osteoarthritis. *Rheumatol. (Oxford)*. **39** (5), 490–496 (2000).
55. Sharma, L. et al. The role of knee alignment in disease progression and functional decline in knee osteoarthritis. *Jama*. **286** (2), 188–195 (2001).
56. Riskowski, J., Dufour, A. B. & Hannan, M. T. Arthritis, foot pain and shoe wear: current musculoskeletal research on feet. *Curr. Opin. Rheumatol.* **23** (2), 148–155 (2011).
57. Tiberio, D. The effect of excessive subtalar joint pronation on patellofemoral mechanics: a theoretical model. *J. Orthop. Sports Phys. Ther.* **9** (4), 160–165 (1987).
58. Lafortune, M. A., Cavanagh, P. R., Sommer, H. J. 3rd & Kalenak, A. Foot inversion-eversion and knee kinematics during walking. *J. Orthop. Res.* **12** (3), 412–420 (1994).
59. Tong, J. W. & Kong, P. W. Association between foot type and lower extremity injuries: systematic literature review with meta-analysis. *J. Orthop. Sports Phys. Ther.* **43** (10), 700–714 (2013).
60. Lathrop-Lambach, R. L. et al. Evidence for joint moment asymmetry in healthy populations during gait. *Gait Posture*. **40** (4), 526–531 (2014).
61. Spector, T. D., Hart, D. J. & Doyle, D. V. Incidence and progression of osteoarthritis in women with unilateral knee disease in the general population: the effect of obesity. *Ann. Rheum. Dis.* **53** (9), 565–568 (1994).
62. Dodelin, D., Tourny, C. & L'Hermette, M. The biomechanical effects of pronated foot function on gait. An experimental study. *Scand. J. Med. Sci. Sports*. **30** (11), 2167–2177 (2020).
63. Buldt, A. K. et al. Foot posture is associated with plantar pressure during gait: a comparison of normal, planus and cavus feet. *Gait Posture*. **62**, 235–240 (2018).
64. Paterson, K. L., Clark, R. A., Mullins, A., Bryant, A. L. & Mentiplay, B. F. Predicting dynamic foot function from static foot posture: comparison between Visual Assessment, Motion Analysis, and a commercially available depth camera. *J. Orthop. Sports Phys. Ther.* **45** (10), 789–798 (2015).
65. Li, H. et al. Gait analysis of bilateral knee osteoarthritis and its correlation with WesternOntario and McMaster University Osteoarthritis Index Assessment. *Med. (Kaunas)* **58**(10), 1419 (2022).
66. Melai, T. et al. Calculation of plantar pressure time integral, an alternative approach. *Gait Posture*. **34** (3), 379–383 (2011).
67. Sauseng, S., Kästenbauer, T., Sokol, G. & Irsigler, K. Estimation of risk for plantar foot ulceration in diabetic patients with neuropathy. *Diabetes Nutr. Metab.* **12** (3), 189–193 (1999).
68. Waaijman, R. & Bus, S. A. The interdependency of peak pressure and pressure-time integral in pressure studies on diabetic footwear: no need to report both parameters. *Gait Posture*. **35** (1), 1–5 (2012).

Author contributions

YW, TJ, and YG Z designed this study. YW and TJ conducted the assessments. YW, TJ, and PM Z collected the data and conducted the statistical analysis. YW and PM Z wrote the original draft. GC C, TJ, and YG Z critically revised the article for important intellectual content. All authors reviewed and approved the final version to be submitted.

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Declarations

Competing interests
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