Static Plantar Pressure Distribution and Position Correlations in Early and Mid-term Knee Osteoarthritis Patients

Wan Yiqun[1], Gao Weiyu[2], Wang Lixin[1], Wang Ruiyue[3], Yang Zhikai[4], Wang Xin[1]

Abstract

Background: Knee osteoarthritis (KOA) is the most common degenerative joint disease, and patients will develop abnormalities in the movement model. Plantar pressure distribution and body postural characteristics may differ in patients with KOA compared to healthy adults and may affect physical function in these patients. At present, most related studies focus on patients with advanced KOA, and there are few studies on patients in early and middle stages. This study aims to apply the plantar pressure detection and human joint point identification technology to explore the characteristics of body posture and plantar pressure distribution in the early and middle-term KOA patients.

Materials and Methods: Data from 38 middle and early KOA patients (age =54.58 ± 7.32 years) and 28 healthy volunteers (age =54.93 ± 7.90 years) including, lower limb weight bearing, peak foot pressure distribution, pressure center (center of pressure [CoP]) offset, offset area, Q angle, pelvic position, spine offset, and other data were compared by statistical analysis of independent sample t-test and Pearson's Chi-square test.

Result: The results showed that the foot pressure in the early and mid-term KOA patients tended to be distributed in the medial heel, and the body CoP swing range was smaller than that in the control group ($P < 0.05$). In addition, patients in the KOA group had a larger left Q angle than the control group and had a smaller rate of right pelvis bias ($P < 0.05$). There was no statistical difference in lower limb weight bearing and spinal posture between the two groups.

Conclusion: In standing conditions, patients in the KOA group have exhibited abnormal postural patterns and foot pressure distribution in the early and middle stages compared with healthy volunteers. Assessment of plantar pressure distribution, pelvic position, and positioning of lower limb joints may be important for evaluating patients with KOA.

Keywords: Knee osteoarthritis, Plantar pressure, Posture

Introduction

Knee osteoarthritis (KOA) is the most common degenerative joint disease, with an annual global incidence of 2.03% [1]. The number of people over 60 years old living with KOA in China may have reached 15 million [2]. KOA not only causes structural damage and pain to the knee joint but also functional damage in the early stages, affecting the quality of life of patients [3,4]. Many scholars believe that its development is related to the abnormal load caused by the uneven lower limb joint alignment [5,6].

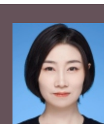
The early identification and intervention in KOA can help to restore the joint homeostasis, improve the prognosis, and even delay the development of arthritis [7,8]. The foot is the only part of the body in contact with the ground when standing. The plantar pressure detection technology can help to evaluate the ground movement pattern, the characteristics of the plantar pressure distribution, and the weight-bearing changes in the lower limbs. This technique has been widely used in the evaluation of postural stability, and the diagnosis and treatment of patients with diabetic foot and stroke [9,10]. Modeling the different limb structures of the human body contributes to the evaluation of human bone joints and motion analysis [11].

The technology is still in the development stage. After continuous updating and iteration, the accuracy to evaluate human joints has gradually improved [12]. It is progressively beginning to be applied in sports training, sports function evaluation, sports injury protection, efficacy evaluation, and other fields [13-15].

At present, more and more scholars are applying these techniques to study and improve knowledge about the function of patients with KOA [16,17], but the most studies have focused on patients with advanced osteoarthritis. Few studies target

[1]Department of Orthopaedic Medicine, Institute of Orthopedics, Fourth Medical Center of PLA General Hospital, Beijing, China,
[2]Geriatrics Center, The People's Hospital of Inner Mongolia Autonomous Region, Hohhot, China,
[3]College of Nursing and Rehabilitation, North China University of Science and Technology, Qinhuangdao, China,
[4]Department of Rehabilitation, Capital Medical University Electric Teaching Hospital/State Gird Beijing Electric Power Hospital, Beijing, China.

Address of Correspondence
Dr.Wang Xin,
Department of Orthopaedic Medicine, Institute of Orthopedics, Fourth Medical Center of PLA General Hospital, Beijing, China.
E-mail: wangx126@126.com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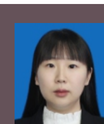
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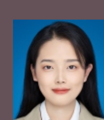
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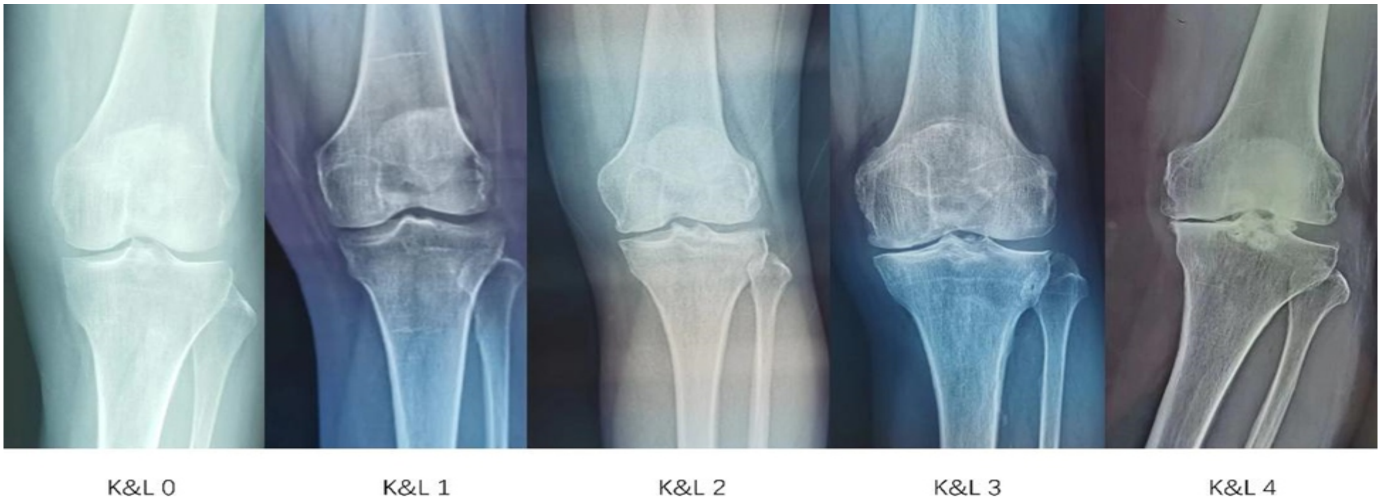

Figure 1: K&L Classification: 0: Normal, 1: Doubtful narrowing of joint space and possible osteophytic lipping, 2: Definite osteophytes and possible narrowing of joint space, 3: Moderate multiple osteophytes, definite narrowing of joint space, some sclerosis, and possible deformity of bone ends, 4: Large osteophytes marked narrowing of joint space, severe sclerosis, and definite deformity of bone ends.

Figure 2: Diagram of static plantar pressure zones.

early and middle-term patients. At the same time, the application of deep learning-based human joint point identification technology also provides a more convenient and safe way to detect joint alignment and body posture in patients with KOA.

Materials And Methods

Ethical statement

The current investigation received approval from the Clinical Trial Medical Ethics Committee at the Fourth Medical Center of PLA General Hospital, under Ethics Approval No. 2022KY059-KS001, and followed the principles stated in the Declaration of Helsinki. Before their involvement, all participants were duly informed about the study's objectives and content and provided their consent by signing informed consent documents.

Participants

The recruitment of participants for this study took place at the hospital from February 2023 to June 2023. Individuals who fulfill the following requirements were invited to participate (Table 1): (a) Age ranging from 40 to 70; (b) no significant lower limb joint trauma experienced within the past year; (c) no surgical procedures performed on the lower extremity joints in the last year; (d) absence of other medical conditions such as rheumatoid arthritis, stroke, scoliosis, or any other ailments affecting quality of life and lower limb function unless they have been stable for at least 6 months; (e) expressing willingness to understand and actively participate in this study. A total of 128 patients and volunteers meeting these criteria were recruited.

Suitable participants were then evaluated based on predetermined criteria to determine their eligibility. Participants who met the following criteria were included in the KOA group (Table 2): (a) Experiencing symptoms in both knee joints for over 3 months; (b) having morning stiffness in the knee joint; (c) exhibiting joint line tenderness and crepitus during the specialist examination; (d) having a Kellgren-Lawrence (K&L) grade ranging from 0 to 3 on imaging evaluation; and (e) having a body mass index (BMI) of ≤28 kg/m2 [18, 19].

Exclusion criteria in the KOA group included (Table 3): (a) Inconsistent K&L grades

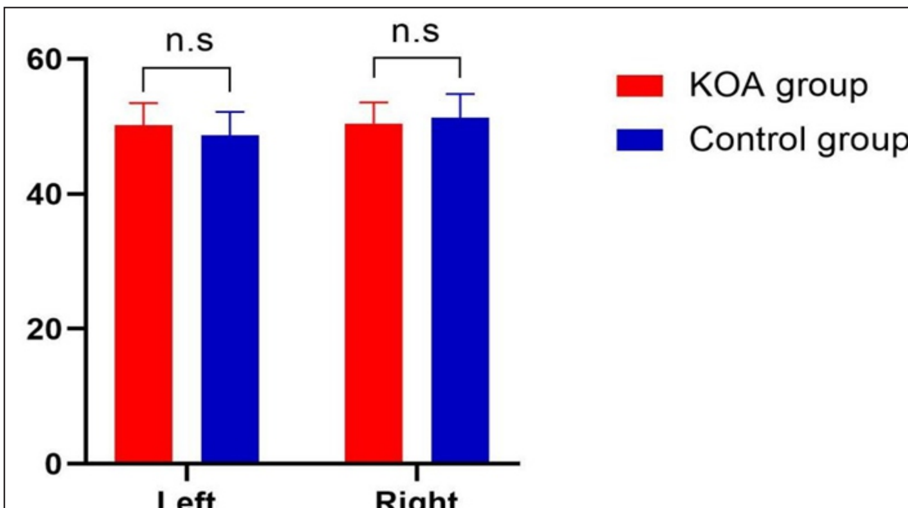

Figure 3: Weight-bearing of both lower limbs. *: $P<0.05$, * *: $P<0.01$, n.s: no statistical difference.

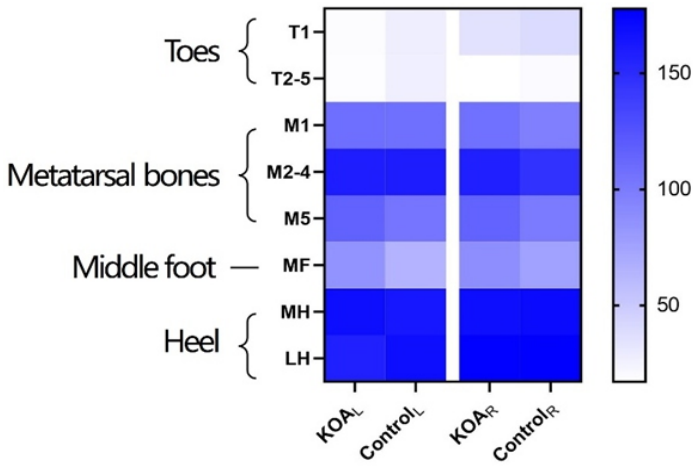

Figure 4: Pressure in each region of the foot.

between both knees on imaging evaluation; (b) BMI <20 kg/m2; and (c) severe limitation of knee joint activity hindering independent participation in a full set of assessments.

Participants who met the following inclusion criteria were included in the control group (Table 2): Inclusion criteria consisted of: (a) Absence of knee pain within 1 year and (b) BMI ≤28 kg/m2.

Exclusion criteria for the control group involved (Table 3): (a) Inability to independently complete a full set of assessments due to various reasons and (b) BMI <20 kg/m^2.

Equipment

In the study, we used a plantar pressure and the body posture analysis system to evaluate the static plantar pressure. The system contains an embedded force plate with a 48 HV matrix sensor, a far infrared HD camera, and an attitude software analysis host. The load plate has 2304 (48 × 48) matrix piezoresistance sensors, a data acquisition frequency of 86 HZ: HD camera resolution 1280 x 1024, an image acquisition frame rate of 30 FPS, and the minimum unit of mm.

Evaluation

KOA staging

This study was based on the K&L classification [20] (Fig. 1), symptomatic manifestations, and limited activity in KOA patients [4].

KOA was divided into early, middle, and late stages:

a. Early stage: Mild-to-moderate pain with movement, no significant deformity, fair joint movement, K&L grade 0 or 1.

b. Medium-term: Limited mobility due to severe pain, deformity, and joint instability, K&L grade 2 or 3.

c. Late stage: K&L is grade 4 due to severe pain, significant deformity, and significant limitation of joint movement.

Measurement of foot pressure and body posture parameters

Subjects were required to wear shorts and short sleeves and stand barefoot on the measuring table for plantar pressure testing. In the natural standing position, the subject is required to look at the front, feet, and shoulder width, and the upper limbs naturally hang on both sides of the body. Plantar pressure acquisition continued for 5s. After the foot pressure is collected, the patient is required to step back 2 m away from the front of the camera and take photos of the front, side, and back of the patient after identifying the human joints respectively. The identified body posture images will be analyzed in the posture software analysis platform.

Data analysis

Plantar pressure-related parameters

Weight-bearing in both lower limbs was expressed as a percentage of body weight. The body center of pressure (CoP) offset at the maximum distance (maximal distance) and the oval area (elliptic area) is used to evaluate the swing amplitude of the body center of gravity during static standing. To better evaluate the characteristics of the plantar pressure, foot pressure into eight areas was evaluated through the system (Fig. 2): hallux (T1), toes 2–5 (T2-5), first metatarsal bone (M1), second to fourth metatarsal bones (M2-4), fifth metatarsal bone (M5), middle part of the foot (MF), medial heel (MH), and lateral heel (LH). The mean foot pressure for each region and the distribution of peak foot pressure was also measured.

Postural-related parameters

In this study, the posture of the sagittal spine was evaluated by measuring the amplitude of head advancement and thoracic kyphosis, and the pelvic position was counted and classified as pelvic neutrality, pelvic forward tilt, and pelvic backward tilt according to the algorithm. The posture on the coronal plane was assessed by measuring the magnitude of the left and right head deviation and the degree of high and low shoulders. In the study, when we count the magnitude of the head offset, we assume that the head right offset value is positive, and then the left offset value is

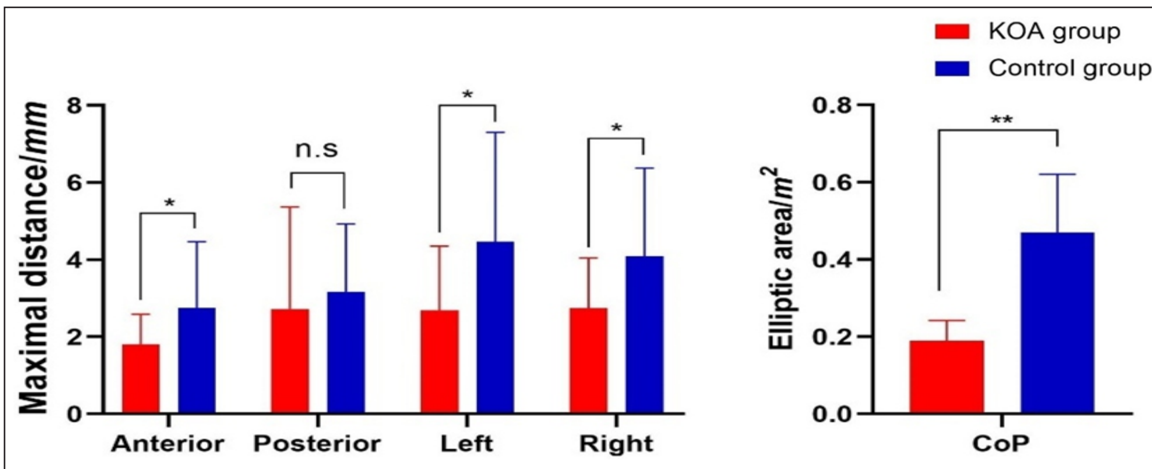

Figure 5: CoP offset. *P<0.05, **P=0.01, n.s: no statistical difference.

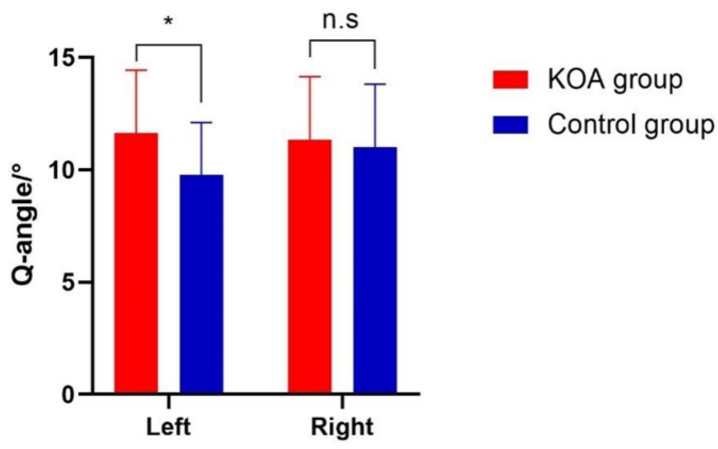

Figure 6: Q Angle difference. *P<0.05, **P<0.01, n.s: No statistical difference.

negative. The degree of high and low shoulders (high and low shoulders) is evaluated by the difference between the height of the left and right shoulder joints. If the right side is higher, the value is positive, and if the left side is higher, the value is negative. At the same time, we also counted the amplitude of the left and right tilt of the coronal pelvis and evaluated it by comparing the height difference of the anterior superior iliac spine on both sides. If the right is higher, the value is positive, and if the left is higher, the value is negative.

Data analysis

The data analysis was performed using SPSS 27.0 software. An independent sample T-test was used to compare quantitative variables among different groups, while Pearson's Chi-square test was employed for analyzing categorical variables.

Results

Demographic Information

A total of 66 participants (KOA group = 38, Control group = 28) were enrolled in this study after receiving comprehensive information about the research and giving informed consent, along with signed commitment forms. Within the KOA group, there were 22 individuals with early-stage KOA and 16 individuals with moderate-stage KOA (Table 4). The demographic information showed no significant differences between the two groups ($P > 0.05$), suggesting a high level of similarity within the study population.

Weight-bearing condition of the lower limbs

This study evaluates the distribution of body weight in the plantar area to assess lower limb weight bearing, expressed as a percentage. As shown in Fig. 3, the weight bearing of the KOA group and the control group was about 50% of their body weight, with no statistical difference ($P < 0.05$).

Statistical table of foot pressure distribution

As shown in Fig. 4, the left foot pressure of 2–5 toes was less than the control group, and the MH, LH, and 2–4 metatarsophalangeal joints were greater than the control group ($P < 0.05$). The mean foot pressure data of left foot and heel also showed that the KOA group was greater than that in the control group, and the mean foot pressure of 2–5 toes in the KOA group was less than that in the control group, but there was no statistical difference ($P > 0.05$).

The double full pressure peak is mainly distributed in the MH, LH, the first metatarsophalangeal joint, 2–4 metatarsophalangeal joints, and the fifth metatarsophalangeal joint. The peak distribution of foot pressure in both subjects was mainly distributed in the heel (Table 5), but only the right foot distribution was statistically different ($P < 0.05$): 78.9% of the KOA subjects had peak foot pressure in the MH, and none in the first and fifth metatarsophalangeal joint areas. The control pressure was distributed in all three areas of the heel and metatarsophalangeal joints, with the largest proportion in the MH, but not exceeding 50%.

As shown in Fig. 5, elliptical area of CoP and CoP moving tracks in KOA subjects was significantly less than that in the natural standing position, $P < 0.05$). The offset amplitude of the CoP forward, left, and right in the KOA group was also significantly smaller than that in the control group ($P < 0.05$).

Joint alignment of the lower limbs

For the positioning of the lower limb joint, the study mainly evaluated the difference in

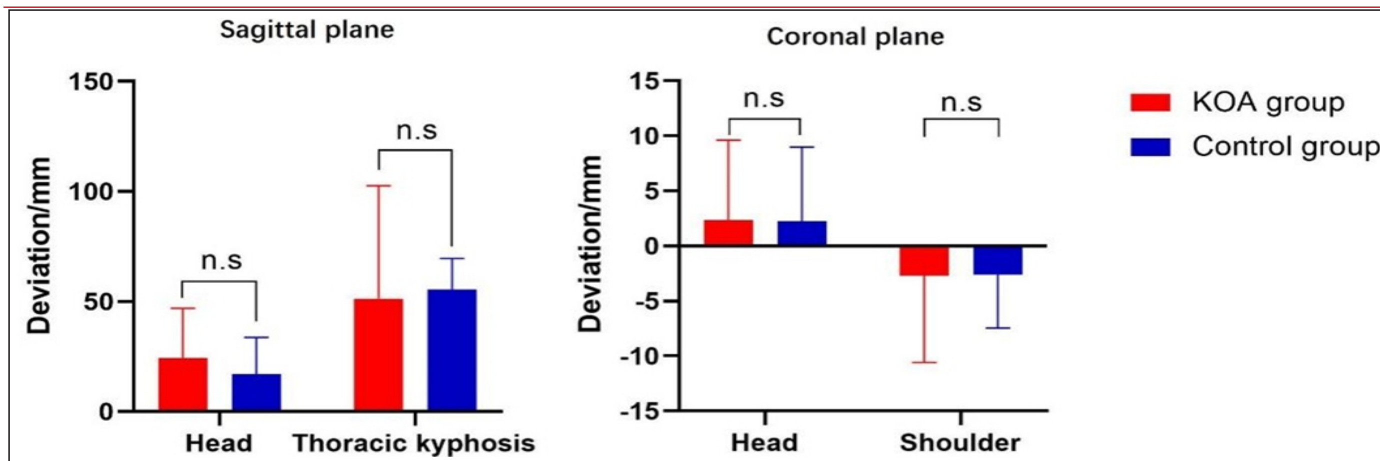

Figure 7: Sagittal pelvic spinal posture. The offset amplitude of the sagittal spine posture is the deviation of the spine on sagittal plane. *P<0.05, **P<0.01, n.s: No statistical difference.

Table 1: Recruitment criteria
Recruitment criteria
Age 40–70
No history of lower limb trauma or surgical procedures
Absence of other medical conditions such as rheumatoid arthritis, stroke, scoliosis, or any other ailments affecting quality of life and lower limb function unless they have been stable for at least 6 months
Expressing willingness to understand and actively participate in this study

Q angle in the KOA and control groups. The results are shown (Fig. 6), there was no significant difference in the Q angle of the right lower limb between the two groups, while the Q angle of the left lower limb in the KOA group was significantly higher than that in the control group ($P < 0.05$).

Pelvic spinal posture

It was showed that on the sagittal plane, the subjects tended to forward the head and had thoracic kyphosis; on the coronal plane, the head was tilted to the right and the left shoulder was higher than the right shoulder (Fig. 7). However, there was no significant difference in the spinal posture between the two groups ($P < 0.05$).

There was no statistical difference in the pelvic position between the KOA and control subjects (Table 6) ($P < 0.05$), both showed pelvic posture in more than 70% of the subjects. In the coronal plane, 84.6% of the control subjects shifted their pelvis to the right, a proportion significantly greater than that in the KOA group (Table 7) ($P < 0.05$).

Discussion

Some findings suggest that osteoarthritis (OA) in the first metatarsophalangeal joint of the foot is associated with significant changes in the weight-bearing function of the foot, which may lead to the development of secondary pathological changes [21].

The characteristic distribution of pressure and the unique loading of individual foot regions are observed in specific movements [22]. Among them, the different plantar pressure distributions may affect the physical function of the patients. The maximum plantar pressure distribution is different between the OA and control groups [16]. The movement coordination ability of patients with KOA may be impaired. The distribution of human plantar pressure directly reflects the pressure value of each part of the foot when standing or exercising and indirectly feedback the postural control of the knee and even the whole body. The combination of the two can provide the basis and reference for the clinical treatment and rehabilitation of KOA.

Static and dynamic analysis was done using the Footscan® platform system. We investigated the correlation between KOA stage and plantar pressure distribution, where static plantar pressure tended to be distributed on the unaffected side, while dynamic plantar pressure tended to be distributed on both sides. Patients with unilateral KOA have an abnormal plantar pressure distribution closely related to the severity of KOA [23]. It is generally accepted that plantar pressure is closely associated with KOA, whatever KOA grade or stage. The treatment of KOA should not only reduce pain but also trace the source of symptoms to reduce complications and promote the recovery of the overall function of patients.

A study was published in 2021 using a three-dimensional motion capture system that measured gait in 44 patients with advanced KOA and 22 healthy subjects [24]. Patients with KOA exhibit an altered coordination pattern and increased coordination variability of femur-calf and calf-foot. Knee

Table 2: Inclusion criteria	
KOA group	Control group
BMI≤28 kg/m^2	BMI ≤28 kg/m^2
Stiffness of the knee joint in the morning	Free of knee pain within 1 year
Joint line tenderness and crepitus	
K&L Grade 0–3 on radiograph	
Bilateral symptoms for more than 3 months	
BMI: Body mass index	

Table 3: Exclusion criteria

KOA group	Control group
BMI <20 kg/m^2	BMI <20 kg/m²
Inconsistent K&L grades of each knee	Inability to independently complete all assessments due to various reasons

BMI: Body mass index

dysfunction causes altered lower limb co-ordination and unstable motor control during walking [24].

During the progression of KOA, there are three-dimensional changes in gait biomechanics; however, the characteristics and trunk posture according to the severity of OA remain unknown [25]. Due to individual differences, compliance, and cognitive deficiency, there is no consensus on the impact of trunk posture such as high and low shoulders, scoliosis, and pelvic tilt on KOA, and further discussion is needed.

It is particularly interesting to assess how gait patterns in KOA patients are influenced by ground type [26]. Reasonable weight bearing of lower limbs helps to reduce pain, promote overall functional recovery, and increase balance. Abnormal knee loading may cause increased relative subchondral bone mineral density [27]. However, there is no research evidence to show the safety of early weight-bearing activities in KOA patients, so in clinical practice, we should dynamically evaluate to scientifically and carefully master the best timing of lower limb weight-bearing.

Studies have suggested that static alignment is assessed by measuring the hip-knee-ankle angle on long limb imaging [27]. Q angle is the angle describing the relationship between the pelvis, femur, and knee joint. The primary goal of KOA rehabilitation treatment is to reduce pain, and knee varus deformity is a common pathological feature [28]. On this basis, it is necessary to consider the spacing of knee and ankle, knee valgus deformity, and the influence of the spine and pelvis on the assessment of limb function. On this basis, we need parameters to weigh the advantages and disadvantages, and carefully develop rehabilitation and treatment plans.

Severe KOA significantly affected the sagittal alignment of the spinal-pelvic-lower limb axis. The lumbar spine is the primary source of compensation, while hip flexion and pelvic anteversion are increased for further compensation. Changes in the sagittal arrangement may not be involved in the pathogenesis of low back pain in this patient population [29]. KOA causes knee pain leading to sagittal knee deformity and coronary valgus deformity of the lower limbs. Some studies have shown that the changes in lumbar spine disease at L3/4 and L4/5 are associated with the changes in KOA [30]. Patients with KOA have a significant tendency for plantar pressure in the medial forefoot and in the middle or central region of the foot. The COP pattern was shorter and more lateralized in KOA patients, and plantar pressure affecting functional capacity, pain, and well-being in KOA patients [31].

Knee varus is commonly seen in patients with medial KOA, and the foot has a compensatory mechanism for knee varus alignment that becomes valgus. The study found that KOA patients showed more spin pattern than controls, which resulted in abnormal loading in the medial foot, midfoot, and second

Table 4: Demographic information

Variables	KOA (*n* =38)	Control (*n* =28)	*P* -value
Proportion of women	63.20%	57.10%	0.621††
Age (years)	54.58±7.32	54.93±7.90	0.854†
Height (cm)	165.03±6.56	165.17±6.75	0.927†
Body weight (kg)	67.31±7.51	65.50±5.5.73	0.289†
BMI (kg/m^2)	24.67±1.91	24.02±1.81	0.164†
Stage (Early/middle)	22/16	-	-

BMI: Body mass index, †Independent sample t-test, $P<0.05$, ††Pearson's Chi-square test, $P<0.05$

Table 5: Position characteristics of the peak foot pressure distribution

Peak distribution (%)	Left foot		Right foot		P_1 price	P_2 price
	KOA group (*n*=38)	Control group (*n*=28)	KOA group (*n*=38)	Control group (*n*=28)		
Heel inside	5.3	14.3	78.9	42.9	0.317	0.012*
Heel outside	52.6	42.9	15.8	28.6		
The first metatarsal toe joint	7.1	0	0	14.3		
2–4 metatarsophalangeal joints	31.6	28.6	5.3	7.1		
The fifth metatarsal toe joint	10.5	7.1	0	14.3		

P_1: Peak distribution of left foot between KOA and control group Pearson's Chi-square test; P_2: Right foot peak distribution between the KOA and control groups, Pearson's Chi-square test, *Pearson's Chi-square test $P<0.05$

Table 6: The location of the sagittal pelvis

Pelvic position is (%)	The KOA group (*n*=38)	Control group (*n*=28)	P price
The pelvis neutral	21.9	23.1	0.847
anterior tilt of pelvis	78.1	76.9	

Note: P: KOA group and control group, Pearson's Chi-square test $P<0.05$

Table 7: The set of the coronal pelvis

Pelvic offset of (%)	The KOA group (*n*=38)	Control group (*n*=28)	Pprice
Left shift	42.1	15.4	0.024*
Right shift	57.9	84.6	

P: KOA group and control group, Pearson's Chi-square test $P<0.05$

metatarsophalangeal joint [31]. On this basis, the evaluation of plantar pressure is crucial for the comprehensive evaluation of patients with KOA. This information can serve as a basis for designing biomedical devices, and orthoses, to reduce the symptoms of the knee or foot or to reduce the progression of KOA.

Lower limb force line is an important reference index for clinical consideration of the impact on KOA. Foot and ankle problems, with bottom-up effects, can lead to knee valgus, pelvic forward tilt, and scoliosis, a series of effects that foot and ankle surgeons already agree on. Therefore, the improvement of the arch valgus and valgus of the lower limbs improves a series of problems such as pelvic tilt and scoliosis and indirectly treats KOA.

Plantar pressure and gait analysis provides a very necessary basis for early KOA prevention and early improvement of symptoms. It also contributes to the postponement of joint replacement and provides a favorable preparation for joint replacement.

Conclusion

In standing conditions, patients in the KOA group have exhibited abnormal postural patterns and foot pressure distribution in the early and middle stages compared with healthy volunteers. Assessment of plantar pressure distribution, pelvic position, and positioning of lower limb joints may be important for evaluating patients with KOA.

Declaration of patient consent: The authors certify that they have obtained all appropriate patient consent forms. In the form, the patient has given his consent for his images and other clinical information to be reported in the Journal. The patient understands that his name and initials will not be published, and due efforts will be made to conceal his identity, but anonymity cannot be guaranteed.

Conflicts of Interest: Nil. **Source of Support:** None.

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