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RESEARCH

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Medial meniscus injury changed plantar pressure distributions and decreased posture stability especially in those with varus alignment: a cross-sectional study based on a wearable smart plantar pressure system

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Abstract

Background Medial meniscus (MM) injuries are common and often contribute to knee osteoarthritis (KOA). While studies focus on joint degeneration, the role of extrinsic factors such as postural control remains underexplored. This study investigated how MM injuries affected postural control, particularly plantar pressure distribution, with an emphasis on lower limb alignment.

Methods 83 participants were recruited: 29 healthy subjects, 29 MM patients with neutral alignment (-3°< hip-knee-ankle angle (HKA) ≤ 3°), and 25 MM patients with varus alignment (HKA > 3°). Plantar pressure was measured using a shoe-integrated detection system. Normalized peak force, center-of-pressure (COP), and time-to-boundary (TTB) were measured during walking and single-leg stance (SLS).

Results During walking, compared to the healthy group, the varus alignment group showed lower peak force for the posterior heel ($P=0.012$), lateral midfoot ($P=0.024$) and hallux ($P=0.009$). When the two sides were compared, the varus group exhibited a lower peak force in the anterior heel ($P=0.004$) and hallux ($P=0.017$) of the affected sides, the neutral ($P=0.043$) and varus ($P=0.045$) groups all showed higher medio-lateral COP of the unaffected sides, indicating the COP shifting laterally. In SLS test, the two MM groups demonstrated increased peak force of the third ($P=0.037$) and fifth ($P=0.040$) metatarsals compared to the healthy group, the peak force of the posterior heel were lower in the varus alignment group compared to the healthy group ($P=0.007$) and the neutral alignment group ($P=0.008$). And the TTB absolute value of medial-lateral direction of the two MM groups were lower than healthy controls ($P=0.029$). The area under the receiver operating characteristic curve ($AUC=0.698$, $P=0.016$) suggested that peak force of posterior heel had good performance to discriminate varus alignment group from neutral alignment group.

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Conclusion MM injuries, especially with varus alignment, lead to significant changes in plantar pressure distribution and postural stability. These insights are clinically significant for designing early, biomechanically-informed rehabilitative strategies to optimize recovery and prevent further joint degeneration following MM injuries.

Keywords Meniscus injury, Plantar pressure, Limb alignment, Biomechanics, Joint degeneration

Introduction

The meniscus is an essential fibrocartilaginous structure within the knee joint, with significant functions to deepen the tibial plateau, enhance knee joint stability, transmit load through the joint and provide shock absorption [1]. Meniscal injuries are among the most common sports injuries in the knee joint, accounting for approximately 60% of knee injuries, and medial meniscal (MM) injuries are more common than lateral meniscal injuries [2]. Meniscal injuries can accelerate articular cartilage degeneration and may even lead to knee osteoarthritis (KOA), limiting daily activities and participation in sports, and imposing significant social and economic burdens globally. The progression of joint degeneration following meniscal injuries is influenced by various factors, including biomechanical imbalances within the knee joint, metabolic changes and so on [1, 3]. However, most research has focused on investigating intra-articular pathologies to explore the mechanisms of joint degeneration, while early assessments of extrinsic factors, such as overall postural control in patients, remain relatively underexplored [4, 5]. In addition, several studies have shown that rehabilitation could significantly reduce the symptoms of meniscal injury by improving muscle strength and gait, indicating that the postural control was likely to change after meniscal injury [6, 7]. A comprehensive postural evaluation in patients with meniscal injuries might help facilitate early, precise interventions, prevent the onset of KOA, and reduce the societal burden.

Plantar pressure measurement is a valuable clinical tool that helps assess abnormal gait patterns and motor control regarding the lower-extremity and foot disorders and advances the understanding of evidence-based rehabilitation protocols [8, 9]. Many studies have compared plantar characteristics in patients with and without KOA during gait [10, 11]. Recently several studies have also investigated plantar pressure distribution and lower limb alignment in relation to specific surgical interventions for KOA [12, 13]. The varus alignment of the force line is closely associated with injuries to the medial meniscus, and is also a predictor for poor outcome following surgery [14, 15]. Biomechanically, this malalignment shifted the center of knee joint loading toward the medial compartment, increasing compressive stress on the medial meniscus and cartilage, which may accelerate degenerative changes [16]. However, there was no relevant research that assessed the dynamic and static plantar pressure characteristics in patients with meniscal injuries. This may be due to the limited sensitivity of conventional testing methods or the difficulty of laboratory settings to accurately reflect natural gait patterns, making it relatively hard to detect early postural control changes following meniscal injuries. The pressure measuring systems include platform systems and in-shoe measurement systems [17]. The use of conventional platform systems is generally restricted to laboratories, which is unfavorable for outdoor applications and various physical activity conditions, while the in-shoe systems are flexible and used in various studies of gait, therefore plantar pressure can be detected during different tasks performed in different environments [18–21].

The purpose of this study was to investigate the impact of MM injuries on postural control and further analyze the effect of knee alignment on plantar pressure distribution in patients with MM injuries. We hypothesized that plantar pressure distribution in patients with MM injuries was distinct from that in healthy controls, and this difference might be prominent in varus knee patients. Results of this work may uncover a potential new mechanism of joint degeneration after meniscus injury and provide important reference for establishing early and precise rehabilitative strategies for treating MM injuries.

Methods

Study design

This was a cross-sectional study. In the present study, 83 participants were recruited, including 29 healthy subjects, 29 MM patients with neutral alignment and 25 MM patients with varus alignment. The basic characteristics of participants were obtained firstly. Then, patients underwent assessment of limb alignment and clinical evaluations, and were divided according to the hip-knee-ankle (HKA) angle into a neutral alignment group ($-3° <$ HKA$\leq 3°$) and a varus alignment group (HKA$>3°$) [22]. Finally, the plantar pressure characteristics were tested. To collect natural gait and plantar pressure features in various physical activity conditions, a novel smart shoe-integrated sensor system had been applied. Normalized peak force, center-of-pressure (COP), and time-to-boundary (TTB) were measured, and both of dynamic and static pressure distribution during walking and single leg stance (SLS) were analyzed. The experimental flow was shown in Fig. 1.

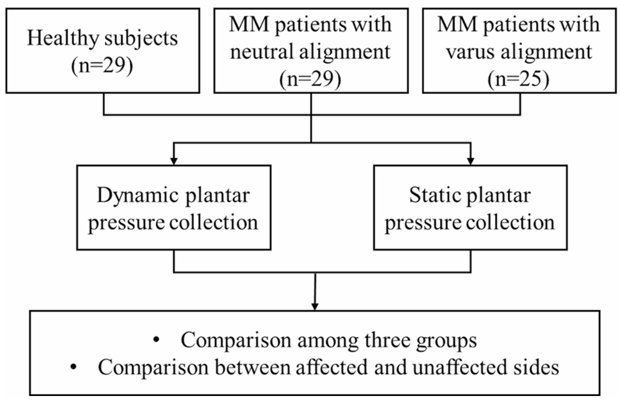

Fig. 1 A flow diagram of the study

Participants
Patients with a unilateral MM tear were recruited. The participants were diagnosed with MM tear by expert orthopedic doctors using MRI. Other inclusion criteria of MM patients were as follows: (1) age between 18 ~ 60 years, (2) neutral alignment of contralateral lower limb; (3) were able to walk independently without the use of an assistive device, and could stand stably for over ten seconds during the stance phase, (4) no concomitant ligament injuries, no signs of osteoarthritis in the affected knee (Kellgren-Lawrence grade 0). MM patients were excluded if they (1) any lesion, surgery, or sign of pathology affecting a lower limb; (2) a history of contralateral lower limb injuries or surgeries; (3) combined with injuries of neurological alterations; (4) foot deformity such as flat feet, Charcot foot, hallux valgus and hindfoot deformity or (5) unwilling to sign informed consent. Healthy subjects were recruited to act as controls, and the inclusion criteria were: (1) aged between 18 ~ 60 years, (2) had no history of knee joint injury or surgery. Exclusion criteria of healthy subjects were: (1) any deformity in knee (such as Genu varum and valgum) or foot deformity; (2) any lower extremity injuries affecting joint activity and diseases of the motor system; (3) unwilling to sign informed consent. All participants had detailed procedures about the study introduced and signed the informed consent forms. This study was approved by the Medical Ethics Committee of the hospital (M2024712).

Equipment
An independently developed novel real-time and low-cost wearable plantar pressure detection system was used to collect regional plantar pressures for both feet at 100 Hz (Fig. 2). The device received a European Union approved Conformity Marking (CE) (CE Certificate Number: B-S210134605), and the reliability and validity have been clinically reported [18, 19]. The system employed multiple graphene-based flexible pressure-sensitive resistors, positioned at the first phalanx (T1), first metatarsal (M1), third metatarsal (M3), fifth metatarsal (M5), medial midfoot (MM), lateral midfoot (ML), anterior heel (HA), and posterior heel (HP) [18, 19]. These sensors were integrated into a flexible printed circuit board and connected to a compact Data Acquisition and Transmission module, which included an Analog Front-End, Analog-to-Digital Converter, microprocessor, and Bluetooth module [18, 19]. This novel shoe-integrated plantar pressure system offered significant advantages for clinical testing, such as portability, ease of use, real-time monitoring capability, and high accuracy. To ensure optimal sensor contact and natural gait patterns, we provided plantar pressure detection shoes in different sizes (sizes from UK4 to UK10) [18].

Assessment of limb alignment
All patients underwent X-ray radiography of both lower extremities in full-length, weight-bearing positions. During imaging, patients were instructed to stand upright with feet together facing forward, knees extended, lower extremities in a neutral rotation position, and patellae pointing directly anteriorly [22]. The HKA angle was used as an evaluation indicator of the lower limb mechanical axis, measured by an experienced physician (Fig. 3). The method for determining the centers of the hip, knee, and ankle was as follows: (1) Center of the femoral head: the center point of the femoral head was determined by the Mose circle method; (2) Center of the knee joint: the midpoint of the line connecting the medial and lateral femoral condyles; (3) Center of the ankle joint: the midpoint of the superior articular surface of the talus [22]. HKA angle was assed as the angular deviation from 180°. HKA angle > 3° for varus alignment, HKA<-3° for valgus alignment, HKA from – 3° to 3° for neutral alignment [12, 23].

For healthy subjects, radiographic analysis was not performed to avoid radiation exposure, while the tibiofemoral angle (TFA) was evaluated with a goniometer to assess the lower limbs line. Skin markers were bilaterally placed at the anterior superior iliac spines (ASIS), center of the patella, and midpoint of the ankle joint. Two longitudinal axes were delineated using a marker pen and a ruler: (1) a femoral axis connecting the ASIS to the patellar center, and (2) a tibial axis linking the patellar center to the ankle midpoint. The goniometer was positioned with its fulcrum at the patellar center, aligning the stationary arm with the femoral axis and the movable arm with the tibial axis. The angle formed at the intersection of these two axes was recorded as the TFA [24, 25].

Clinical evaluations
To comprehensively analyze changes in plantar pressure characteristics and postural control due to structural abnormalities (meniscus injury and varus alignment)

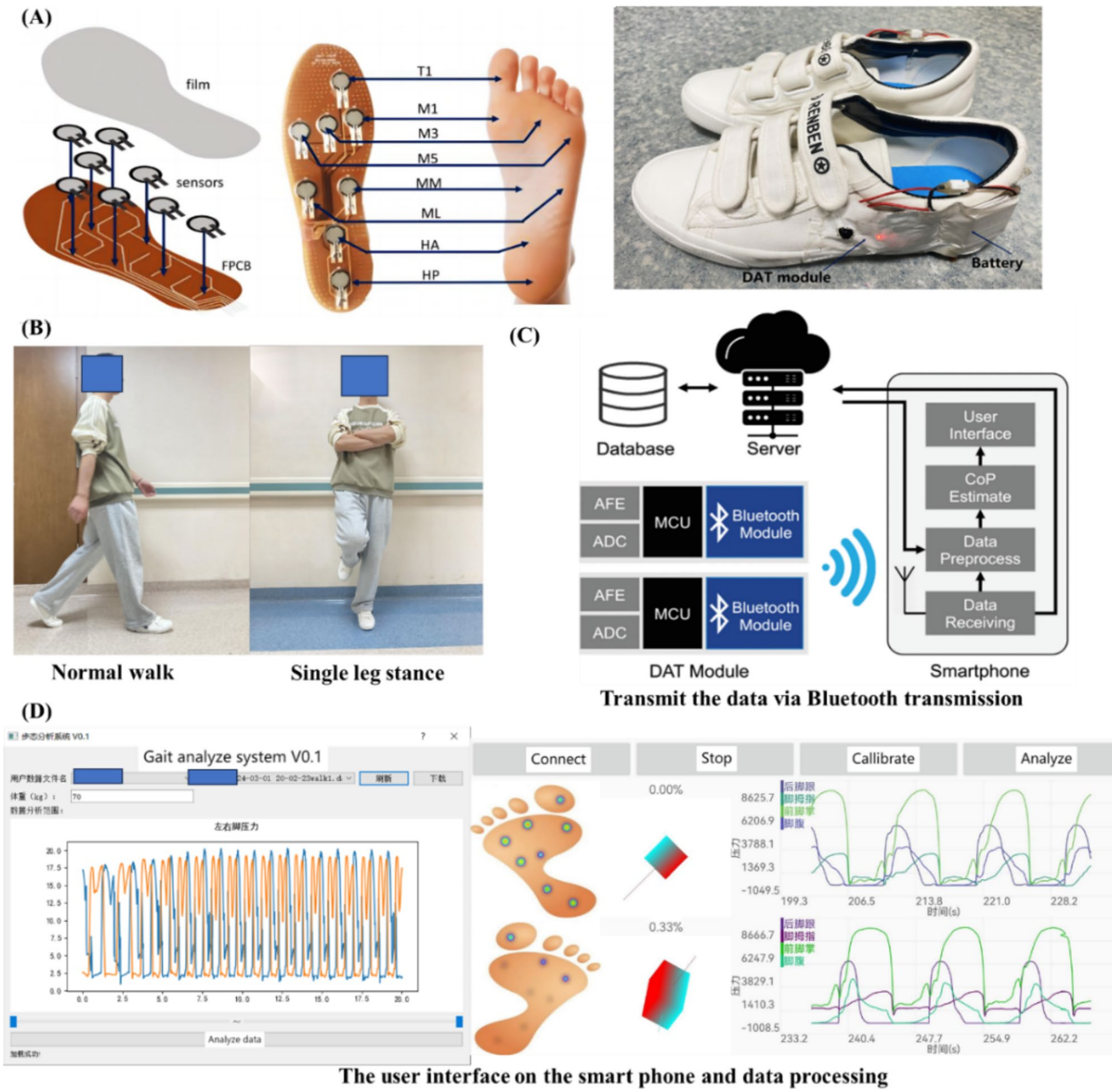

Fig. 2 The user walked on the flat and stand unilaterally with the pressure detection shoes while data were obtained and transformed into a smartphone in time

or pain avoidance mechanisms, the Visual Analogue Scale (VAS) score was included in the evaluation. The VAS (0–10) for average pain occurring in the past week, Knee Injury and Osteoarthritis Outcome Score (KOOS) (0–100), Lysholm Knee Questionnaire (0–100), and Tegner Activity Scale (0–10) were rated by the same investigator to evaluate the clinical functions of the patients.

Plantar pressure analysis

To assess dynamic and static plantar pressure distributions, the walking test and the SLS test were performed. Participants were tested wearing the plantar pressure detection shoes. The sensors were calibrated to ensure accurate data collection. (Fig. 2).

Dynamic test

Before the formal testing of plantar pressure, the participants were instructed to walk at their preferred walking speed while looking forward. To collect natural gait patterns and assess dynamic plantar pressure distributions, each subject walked on a 15 m walkway for 3 trails at a self-selected speed, and the averaged data were used in data analysis [12, 19].

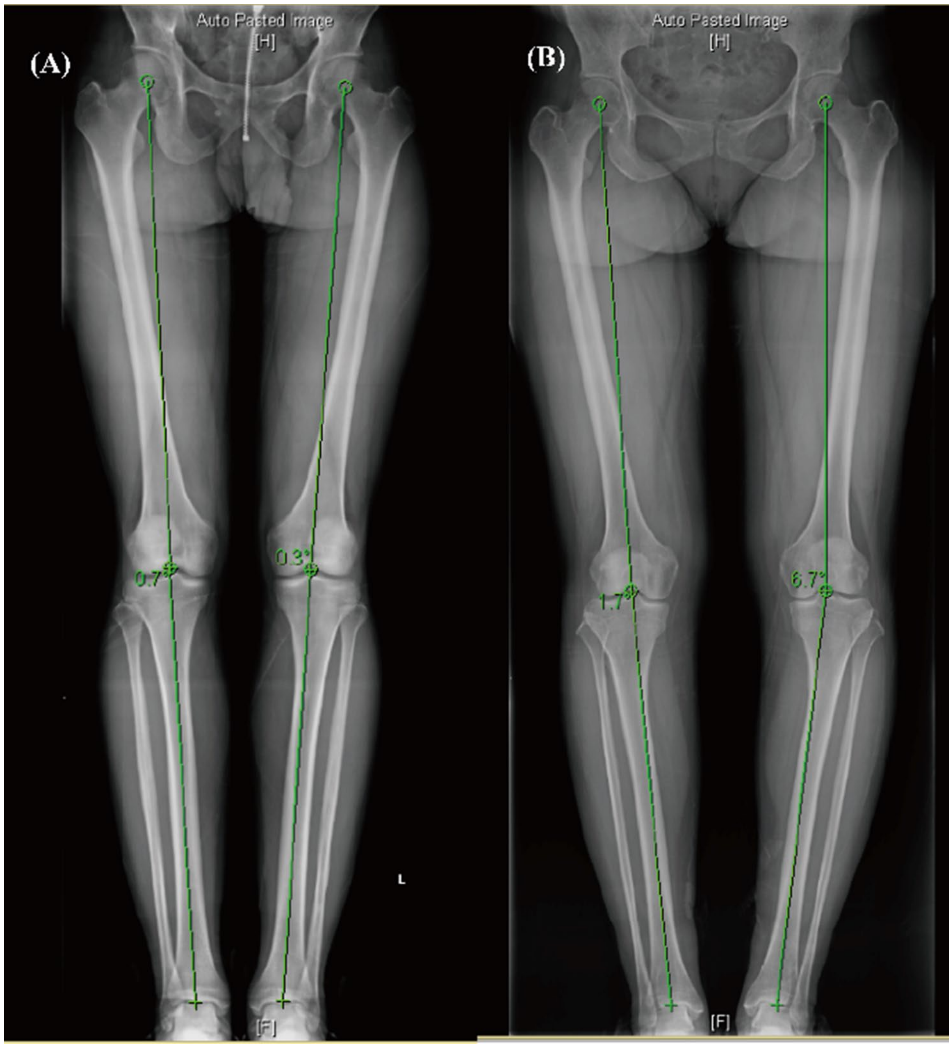

Fig. 3 HKA angle measurement on a full-leg standing anteroposterior X-ray radiograph. (**A**) the neutral alignment, (**B**) the varus alignment. HKA: hip-knee-ankle

Static test

Single leg stance (SLS) was used to assess the static postural control during standing on the injured leg. After standing practice trials, the participants were asked to complete three 10-second trials of single-limb quiet standing on each limb, with their hands in front of their chest and looking forward. The values of the 3 trials were averaged and used for the analysis [26].

Characteristics of plantar load assessment

In the dynamic and static test, the normalized peak plantar force, center-of-pressure (COP) and time-to-boundary (TTB) parameters were evaluated. In this study, the normalized peak force variables (PF%) were calculated as the ratio of the peak force under the region of interest to the body weight [27]. The COP monitoring was performed to quantify the degree of postural sway, including range, variance, and mean velocity of mediolateral (ML) and anterior-posterior (AP) COP excursions [13]. TTB measures the minimum time required for the COP to reach the boundary of the base of support area, reflecting the margin of time or space remaining for an individual to maintain balance [28, 29]. COP and TTB analyze balance and stability from spatial and temporal dimensions, respectively. In this study, TTB variables included the absolute minimum, mean of minimum value, and standard deviation (SD) of minimum value in the ML and AP directions. For the healthy subjects, the dominant leg was chosen for comparison (the preferred leg to kick a soccer) [30].

Raw data processing

To provide a detailed visualization for biomechanical analysis, the plantar pressure maps for both feet were created. Using MATLAB (R2023b), the raw sensor data were processed to calculate mean values and transformed into plantar pressure distribution maps through interpolation and attenuation. The code processed foot contour and sensor data to construct a grid that covers the plantar surface. It then calculated the Euclidean distance from each grid point to the sensors and performed pressure interpolation using a cosine-based attenuation function. Further attenuation was applied to areas near the foot boundaries to account for edge effects, followed by a smoothing procedure to mitigate noise and enhance data clarity.

Statistical analysis

All data was checked for normality through the Shapiro-Wilk test. Normally distributed data were presented as mean ± SD, and categorical data were summarized by frequencies. The Chi-square test was used to compare sex, affected side, and trauma mechanisms. The plantar pressure parameters (PF%, COP, TTB) were analyzed using analysis of variance (ANOVA) method to compare healthy and patient groups, with a Bonferroni post hoc test conducted for significant ANOVA findings. Paired-sample t-tests were used to compare the plantar pressure features between the injured limbs and the non-injured limbs of the patients. Analyses were performed by SPSS (Version 23, Chicago, IL). Statistical significance was set at $P < 0.05$.

Results

Participant characteristics

The demographic data of all groups were presented in Table 1. There were no differences in baseline characteristics among the three groups. For the MM patients, the HKA of the varus alignment group was significantly greater than the neutral alignment group ($P < 0.001$). The both MM patients groups had mild pain, and there were no significant differences in injury characteristics and clinical outcomes. According to the self-reported leg dominance, 24 healthy subjects were right leg dominant, and 5 were left leg dominant. The force alignment of the healthy control group was normal (TFA of the left side: (5.99 ± 1.55)°, TFA of right side was (5.89 ± 1.19)°, $P = 0.774$).

Dynamic plantar pressure characteristics

An example image of the normalized plantar pressure during walking was shown in Fig. 4, and the left side was the affected side. The normalized dynamic plantar pressure distribution of the affected side was shown in Table 2. ANOVA followed by the post hoc test showed that significant differences were between the healthy group and the two MM groups: the MM with varus showed lower peak force for the posterior heel., lateral midfoot and the first phalanx ($P = 0.012$, 0.024, 0.009), and the MM with neutral alignment showed lower peak force for the lateral midfoot ($P < 0.001$). Post hoc comparison revealed no significant difference between the two MM groups, but Cohen's d effect size suggested possible clinically different tendencies (Cohen's d = 0.36, 95% CI: −0.86 to 4.81, $P = 0.170$ for posterior heel; and Cohen's d = -0.38, 95% CI: -1.97 to 0.44, $P = 0.211$ for lateral midfoot; and Cohen's d = 0.38, 95% CI: -1.21 to 4.84, $P = 0.235$ for the first phalanx). When the two sides were compared, peak force of each region was similar between both sides in the MM with neutral alignment group, while the peak force of the anterior heel ($P = 0.004$) and medial midfoot ($P = 0.017$) of the affected side were also significantly lower than the unaffected side in the MM with varus alignment group (Fig. 5).

Table 1 Demographic data for each group

Parameters	Control group (*n* = 29)	MM with neutral alignment (*n* = 29)	MM with varus alignment (*n* = 25)	*P* value
Age (years)	40.14 ± 11.19	45.90 ± 13.61	45.52 ± 12.14	0.152
Gender (male/female, n)	10/9	16/13	13/12	0.392
Height (cm)	171.90 ± 7.34	169.66 ± 9.26	168.96 ± 7.42	0.373
Weight (kg)	69.41 ± 13.15	72.28 ± 13.92	72.56 ± 12.39	0.616
BMI (kg/m^2)	23.34 ± 3.27	25.02 ± 3.73	25.37 ± 3.65	0.080
HKA angle (°)		1.22 ± 0.65	4.97 ± 1.70	< 0.001
Injured side (left/ right, n)		17/12	18/7	0.305
Time since injury (months)		4.50 (2.00, 12.00)	3.00 (1.25, 5.00)	0.239
Trauma mechanism, n				0.344
Sport injury		9	11	
Falling		5	6	
Other		15	8	
Tegner		3.76 ± 1.67	3.91 ± 2.22	0.794
VAS		2.46 ± 1.98	2.83 ± 1.72	0.698
Lysholm		66.64 ± 16.74	66.55 ± 16.89	0.985
KOOS		65.72 ± 13.10	63.05 ± 14.54	0.510

BMI: body mass index; HKA: hip knee ankle

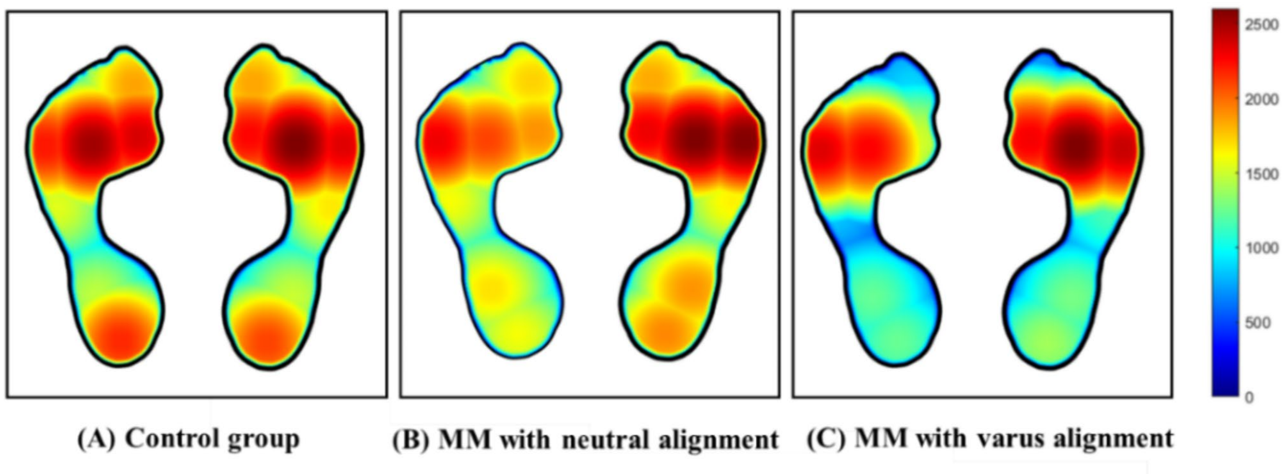

Fig. 4 Representative images of plantar pressure during walking of the three groups. The left side was the affected side

Table 2 Comparison of dynamic normalized peak force (%) between patients and healthy controls

Plantar regions	Control group ($n=29$)	MM with neutral alignment ($n=29$)	MM with varus alignment ($n=25$)	*P* value
HP region	22.74 ± 4.87	20.98 ± 5.14	19.01 ± 5.89[b]	**0.042**
HA region	10.74 ± 3.40	10.47 ± 3.51	10.34 ± 3.11	0.901
ML region	8.69 ± 2.62	6.50 ± 1.82[a]	7.27 ± 2.21[b]	**0.001**
MM region	0.28 ± 0.36	0.47 ± 0.61	0.35 ± 0.55	0.353
M1 region	19.70 ± 7.05	19.70 ± 6.55	20.88 ± 5.24	0.808
M3 region	24.02 ± 6.01	23.28 ± 5.97	23.06 ± 5.47	0.839
M5 region	19.73 ± 4.11	19.53 ± 5.97	19.19 ± 5.10	0.935
T1 region	16.27 ± 6.00	14.01 ± 4.24	12.20 ± 5.16[b]	**0.031**

T1 region: the first phalanx; M1 region: first metatarsal; M3 region: third metatarsal; M5 region: fifth metatarsal; MM region: medial midfoot; ML region: lateral midfoot; HA region: anterior heel; HP region: posterior heel

a: significant differences between the control group and neutral alignment group; b: significant differences between the control group and varus alignment group

Table 3 illustrated the results of COP and COP velocity (COPV) during walking, revealing no significant differences among the three groups. However, in the both MM groups, the medial-lateral COP (COP_ML) of the affected sides was significantly lower than that of the unaffected sides ($P=0.043$, 0.045) (Fig. 6).

Static plantar pressure characteristics

An example image of the normalized plantar pressure during SLS was shown in Fig. 7, and the left side was the affected side. The static plantar pressure distribution was shown in Table 4. ANOVA followed by the post hoc test showed significant differences: compared to the healthy group, the MM with varus alignment group showed lower peak force for the posterior heel ($P=0.007$), and the both MM groups demonstrated increased peak force for the third metatarsal ($P=0.028$, 0.022) and fifth

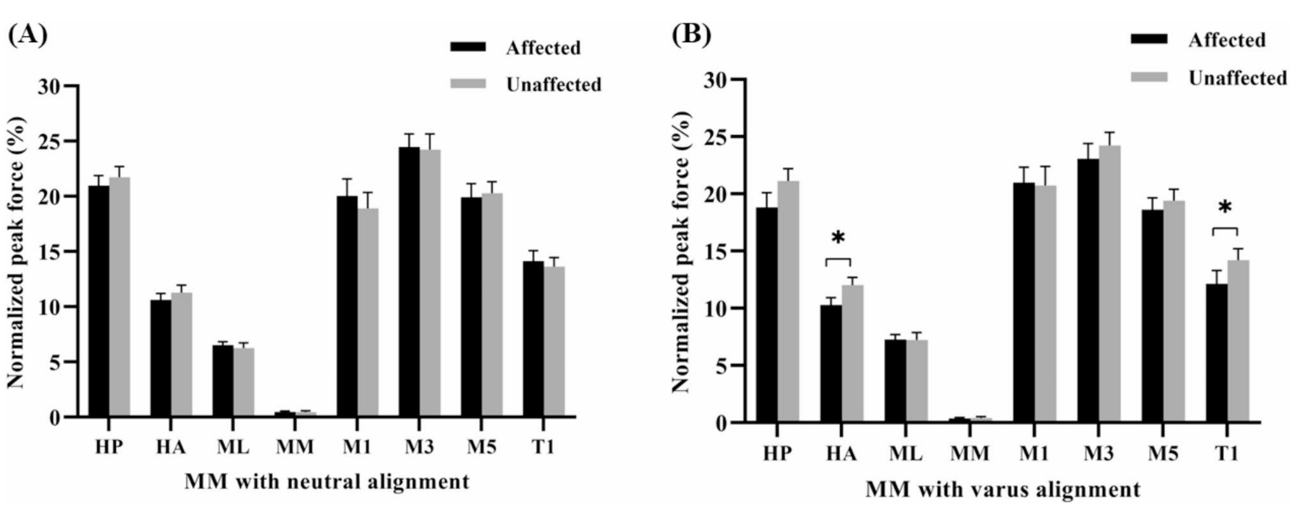

Fig. 5 Comparison of dynamic normalized peak force of the affected and the unaffected side. (**A**) the MM with neutral alignment group; (**B**) the MM with varus alignment group. * Significant differences between the affected sides and unaffected sides

Table 3 Comparison of COP/COPV during walking between patients and healthy controls

Parameters	Control group (n = 29)	MM with neutral alignment (n = 29)	MM with varus alignment (n = 25)	P value
Mean COP_ML (cm)	-0.17 ± 0.38	-0.19 ± 0.32	-0.20 ± 0.40	0.947
Mean COP_AP (cm)	0.83 ± 3.27	0.62 ± 3.69	0.09 ± 4.30	0.761
COP variance_ML (cm)	0.48 ± 0.13	0.47 ± 0.18	0.48 ± 0.18	0.923
COP variance_AP (cm)	4.01 ± 1.16	3.70 ± 1.03	3.46 ± 1.16	0.196
Mean COPV_ML (m/s)	0.06 ± 0.03	0.06 ± 0.03	0.05 ± 0.02	0.681
Mean COPV_AP (m/s)	0.38 ± 0.16	0.33 ± 0.13	0.32 ± 0.12	0.266
COPV variance_ML (m/s)	0.14 ± 0.12	0.14 ± 0.16	0.14 ± 0.17	0.994
COPV variance_AP (m/s)	1.37 ± 1.20	1.04 ± 0.80	1.15 ± 0.89	0.413

COP: center of pressure; COPV: COP velocity; ML: medial-lateral; AP: anterior-posterior

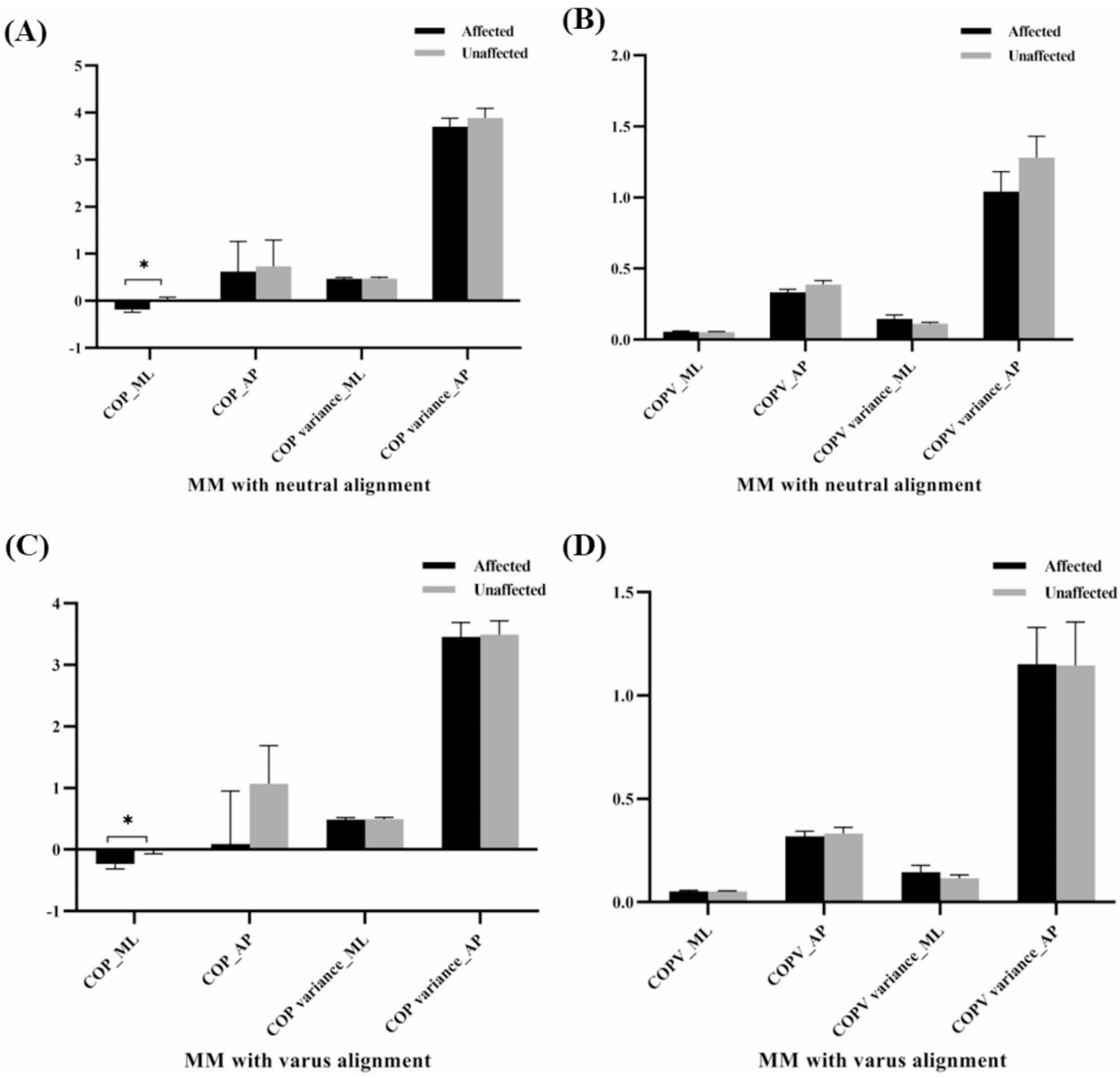

Fig. 6 Comparison of COP and COPV of the affected and the unaffected side during walking. (**A**) COP parameters of the MM with neutral alignment group, (**B**) COPV parameters of the MM with neutral alignment group, (**C**) COP parameters of the MM with varus alignment group, (**D**) COPV parameters of the MM with varus alignment group. COP: center of pressure; COPV: COP velocity; ML: medial-lateral; AP: anterior-posterior. * Significant differences between the affected sides and unaffected sides

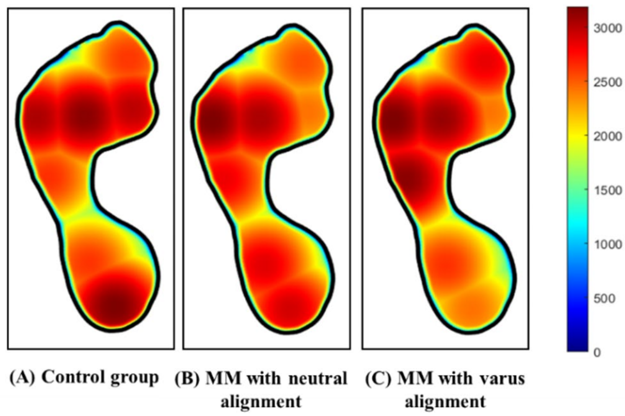

Fig. 7 Representative images of plantar pressure during SLS of the three groups. The left side was the affected side

Table 4 Comparison of static normalized peak force (%) between healthy controls and patients

Plantar regions	Control group (*n* = 29)	MM with neutral alignment (*n* = 29)	MM with varus alignment (*n* = 25)	*P* value
HP region	17.89 ± 4.58	17.78 ± 3.42	14.43 ± 5.11[bc]	**0.009**
HA region	9.94 ± 2.77	10.17 ± 2.75	8.66 ± 2.18	0.097
ML region	11.16 ± 2.48	9.83 ± 2.99	9.74 ± 3.00	0.139
MM region	0.15 ± 0.14	0.25 ± 0.40	0.22 ± 0.42	0.616
M1 region	13.16 ± 3.82	15.27 ± 5.07	14.34 ± 4.33	0.307
M3 region	13.55 ± 4.50	16.74 ± 4.38[a]	16.94 ± 4.66[b]	**0.037**
M5 region	13.96 ± 3.14	16.63 ± 4.10[a]	16.38 ± 3.61[b]	**0.040**
T1 region	9.29 ± 3.36	9.03 ± 4.54	8.96 ± 3.87	0.961

T1 region: the first phalanx; M1 region: first metatarsal; M3 region: third metatarsal; M5 region: fifth metatarsal; MM region: medial midfoot; ML region: lateral midfoot; HA region: anterior heel; HP region: posterior heel

a: significant differences between the control group and neutral alignment group; b: significant differences between the control group and varus alignment group; c: significant differences between the neutral alignment group and varus alignment group

Table 5 Comparison of TTB during SLS between patients and healthy controls

Parameters	Control group (*n* = 29)	MM with neutral alignment (*n* = 29)	MM with varus alignment (*n* = 25)	*P* value
TTB absolute_ML (s)	0.74 ± 0.35	0.49 ± 0.36[a]	0.51 ± 0.39[b]	**0.029**
TTB absolute_AP (s)	1.14 ± 0.69	0.76 ± 0.66	0.88 ± 0.90	0.167
TTB mean_ML (s)	5.09 ± 3.33	5.00 ± 2.91	5.75 ± 4.09	0.718
TTB mean_AP (s)	8.56 ± 4.21	7.00 ± 4.58	6.13 ± 4.88	0.182
TTB SD_ML (s)	6.90 ± 4.82	7.28 ± 5.44	6.82 ± 5.52	0.946
TTB SD _AP (s)	10.76 ± 6.75	9.33 ± 6.91	7.88 ± 6.120	0.332

TTB: time-to-boundary; ML: medial-lateral, AP: anterior-posterior, SD: standard deviation. a: significant differences between the control group and neutral alignment group; b: significant differences between the control group and varus alignment group

metatarsal ($P = 0.020$, 0.036); compared to the neutral alignment group, the MM with varus alignment group showed significant lower peak force for the posterior heel ($P = 0.008$). When the two sides were compared, peak force of each region in the neutral alignment group was similar between both sides; while in the varus alignment group, the peak force of the anterior heel of the affected side were significantly lower than the unaffected side ($P = 0.030$), and the peak force of fifth metatarsal ($P = 0.035$) of the affected side were significantly higher than the unaffected side (Fig. 8).

The TTB parameters during SLS in all groups were shown in Table 5. ANOVA followed by the post hoc test showed that significant differences were between the healthy group and the two MM groups: the TTB absolute_ML were significantly lower in the two MM groups than in the healthy group ($P = 0.014$, 0.033). When the two sides were compared, the TTB absolute_ML, TTB absolute_AP and TTB mean_AP of the affected sides were significantly lower than that of the unaffected sides

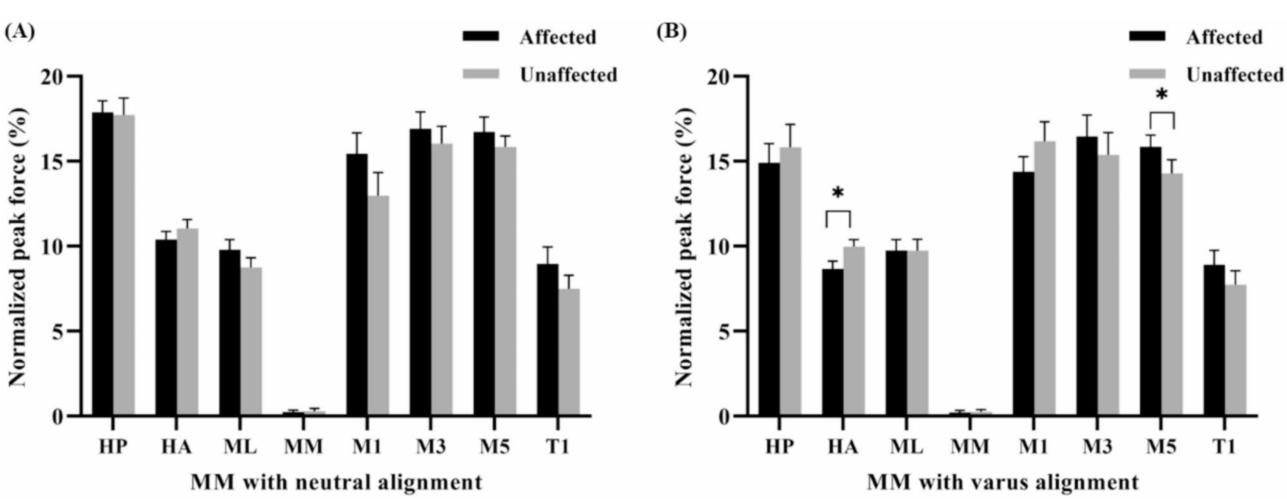

Fig. 8 Comparison of static normalized peak force of the affected and the unaffected side. (**A**) the MM with normal alignment group, (**B**) the MM with varus alignment group. * Significant differences between the affected sides and unaffected sides

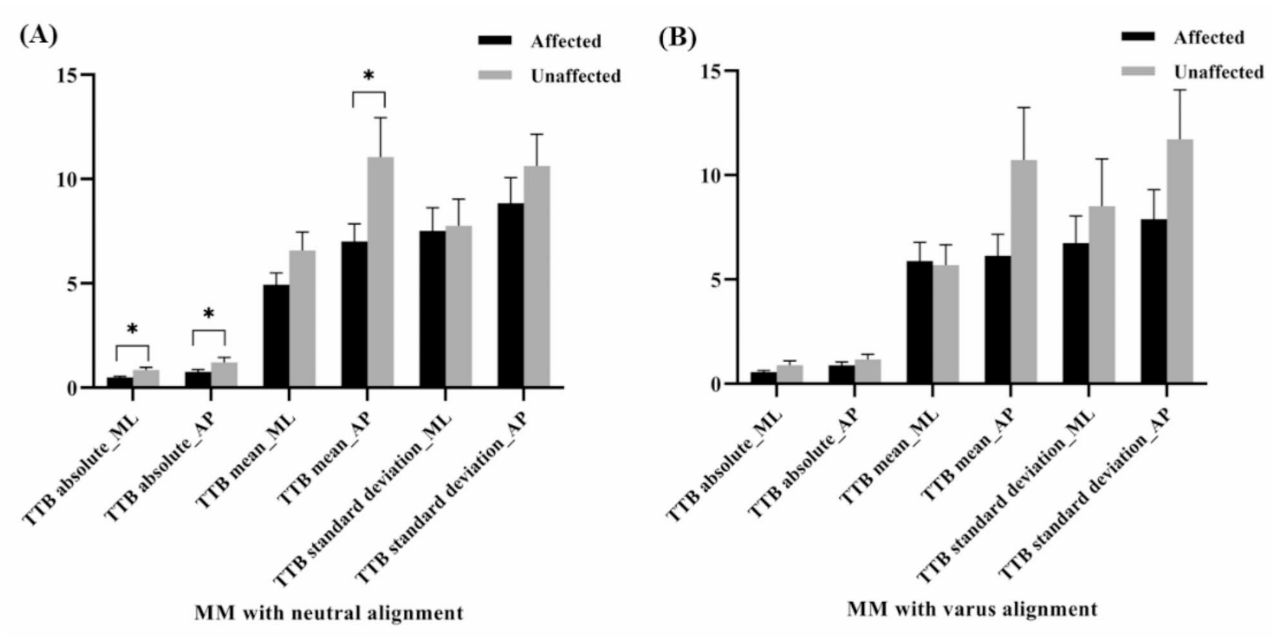

Fig. 9 Comparison of TTB of the affected and the unaffected side during single leg standing. (**A**) TTB parameters of the MM with neutral alignment group, (**B**) TTB parameters of the MM with varus alignment group. TTB: time-to-boundary; ML: medial-lateral, AP: anterior-posterior, SD: standard deviation, * Significant differences between the affected sides and unaffected sides

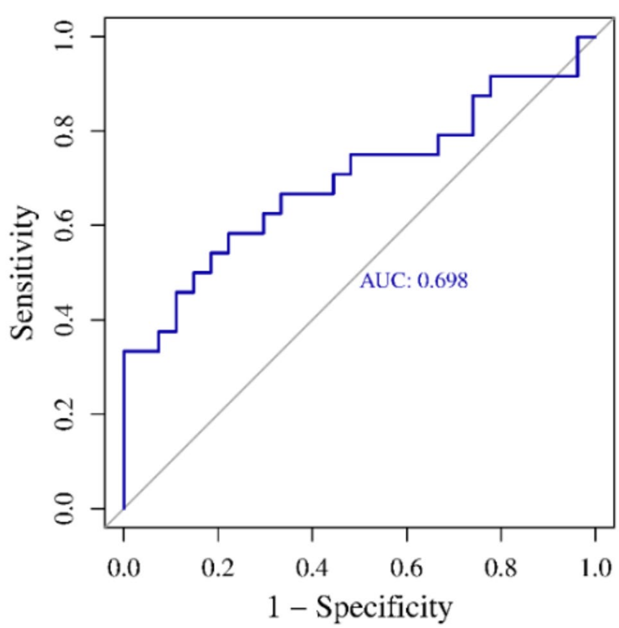

Fig. 10 Receiver operator characteristic curve for normalized peak force of posterior heel during SLS

in the neutral alignment group ($P = 0.005$, 0.020, 0.016), while TTB parameters were similar between both sides in the varus alignment group (Fig. 9).

Receiver operator characteristic (ROC) curve analysis

A ROC curve analysis to delineate the clinical significance of dynamic and static plantar pressure features in MM patients. An area under curve (AUC) > 0.65 indicated a potential diagnostic value of a certain indicator for the disease. Peak force of posterior heel during SLS (AUC = 0.698, $P = 0.016$, cut-off point = 15.32) represented an ability to discriminate MM patients with neutral and varus alignment (Fig. 10).

Discussion

This study utilized a novel portable wearable plantar pressure detection system to investigate the plantar pressure characteristics during walking and SLS in patients with MM injuries, with a particular focus on how lower limb alignment affects these characteristics. The results indicated that during walking, patients with normal alignment exhibited relatively normal plantar pressure distribution compared to healthy controls, while those with varus alignment showed more pronounced abnormalities, characterized by reduced pressure in the rearfoot and forefoot. During SLS, MM patients demonstrated a lateral shift in plantar pressure distribution, particularly in those with varus alignment. Additionally, mediolateral stability was reduced in MM-injured patients, and varus alignment may also influence the stability and postural control of the contralateral unaffected limb.

The demographic data showed there were no differences in baseline characteristics among the three groups. According to related studies, the dominant leg of healthy subjects was chosen for comparison, and for the MM patients, the affected side was chosen instead the limb dominance [13]. Our analysis focused on unilateral meniscal injury-induced biomechanical adaptations, which likely dominated postural control alterations. Although limb dominance was known to affect lower limb biomechanics, prior evidence suggested that meniscal injury itself induced compensatory strategies that overshadow subtle dominance-related effects in short-term assessments [31, 32]. Previous studies demonstrated that BMI may influence gait parameters, particularly in obese individuals (≥30 kg/m^2) [33, 34]. In this study, there was no significant difference in BMI among the three groups. This suggested that the observed changes in plantar pressure were not primarily driven by BMI differences. However, future studies may benefit from stratifying participants based on BMI (e.g., normal weight, overweight, and obese) to further explore its independent effect on plantar pressure distribution for MM patients.

During walking, MM patients with varus alignment exhibited more pronounced abnormalities in plantar pressure distribution, with reduced pressure in both the rearfoot and forefoot. This finding was consistent with previous research indicating that varus alignment increased stress on the knee joint and may contribute to poor clinical outcomes. Norio Goto et al. retrospectively analyzed the MRI images of 190 patients and found that varus alignment factors were significantly related to medial meniscus extrusion distance (3 mm and above) especially in extruded meniscus knees as osteoarthritis grade progressed [35]. Our study suggested that varus alignment affected the plantar pressure characteristics in MM patients, and this gait pattern aligned with biomechanical adaptations to mitigate excessive medial knee joint loading, a hallmark of varus alignment [36]. The primary function of the hindfoot was weight-bearing. In the varus alignment group, the reduced hindfoot pressure during heel strike may reduce impact forces transmitted to the medial compartment, which may be a gait strategy to alleviate pain during walking [12]. While the hallux pressure reflected compromised propulsion efficiency. Reduced hallux pressure further correlated with decreased ankle plantar flexor activity during terminal stance [37]. These findings emphasized the critical role of lower limb alignment in altering plantar pressure dynamics and gait efficiency in MM patients.

In addition to these dynamic changes in plantar pressure, this study also assessed static postural control during SLS. In varus alignment MM group, the increased plantar pressure of M3, M5 and decreased plantar pressure of HP showed increased loading on the forefoot and lateral side during SLS, possibly due to altered knee mechanics that shift the load outward. According to Chonglin Yang et al., varus knee could lead to increased lateral plantar pressures as part of compensatory adjustments, and abnormal leg alignment was compensated by the forefoot and midfoot in the latter half of the gait cycle [38]. In the normal alignment MM group, plantar pressure distribution during SLS was similar with the healthy individuals. Hall et al. also reported no significant differences in static plantar pressure in KOA patients without significant alignment deviations [39]. This suggested that abnormal particularly in varus, lead to compensatory changes in static pressure distribution, which could be targeted during rehabilitation.

Both dynamic and static assessments also revealed reduced mediolateral stability in MM patients, particularly in those with varus alignment. In the neutral and varus MM group, COP_ML of the unaffected sides were all significantly larger than the affected sides, which indicated the COP shifting laterally. The lateral shift in the COP during walking, particularly in the varus-aligned group, aligned with previous findings that reported compensatory strategies in KOA and other lower limb disorders [40, 41]. The TTB absolute_ML of the two MM groups were lower than healthy controls, indicating decrease in mediolateral stability, which could increase the risk of falls or further injury [18]. Michelle Hall et al. have also explored the TTB in ACL reconstruction (ACLR) patients, and found that ACLR leg had a lower medial-lateral TTB and medial-lateral TTB normalized to stance time compared to the non-ACLR leg during stair descent [42]. Notably, TTB parameters were similar between both sides in the varus alignment group, which might reflect that the anteroposterior and mediolateral stability in the non-affected leg was also reduced. These results underscored the need to address both affected and unaffected limbs during rehabilitation to improve overall stability and prevent further complications.

The portable plantar pressure detection system used in this study offered clear advantages over traditional stationary devices, particularly in clinical applications. Unlike lab-based systems that limit patient movement, this wearable system enabled real-time monitoring during dynamic and static tasks, offering a more accurate reflection of plantar pressure features in participants [43]. Studies have validated this shoe-integrated sensor system, demonstrating its accuracy and sensitivity in detecting subtle changes in plantar pressure and postural control, even in complex conditions such as chronic ankle instability and long-term COP evaluation [18, 19].

This study underscored the critical role of alignment-specific rehabilitation strategies in optimizing recovery, enhancing stability, and mitigating the risk of long-term joint degeneration in MM patients. For individuals with varus alignment, targeted interventions such as lateral wedge insoles were commonly prescribed to decrease the knee adduction moment and redistributing joint loads [44]. Additionally, strengthening the peroneus longus and posterior tibial muscles was vital for enhancing push-off strength during gait [30]. Bilateral lower limb strength and balance training further contributed to improving postural control and overall stability. While, for MM patients with neutral alignment, emphasis could be placed on balance and coordination training to address potential stability challenges despite fewer alignment-related issues. These tailored rehabilitation approaches were crucial for preventing the progression of KOA following MM injury [45, 46].

To the best of our knowledge, this was the first study to comprehensively examine the impact of MM injuries on stability and postural control, specifically through the analysis of plantar pressure distribution during both walking and SLS. The novel wearable smart plantar pressure system employed in this study offered significant advantages, including rapid testing, flexibility, and high accuracy. These results suggested that alignment-specific rehabilitation strategies could be crucial in improving stability and reducing long-term joint degeneration in MM patients.

There were several limitations in this study. First, it did not categorize the types of MM injuries (such as horizontal tears, vertical tears, or complex tears). Given that this research was designed as an initial exploration into the trends of postural control changes following MM injuries, we did not differentiate between injury types to maintain a broad focus. Future research should classify tear types to assess their specific impact on postural stability and gait. Second, the broad age range might introduce significant variability in musculoskeletal biomechanics, and we did not perform subgroup analysis for age. The study involved a broad age range, which was chosen to keep the study's focus general and exploratory, while also providing preliminary insights across a wide demographic. Future studies could be stratified by age to draw more specific conclusions. Third, the participants in this study were asked to walk at a self-selected speed, and these values in healthy subjects might be faster when compared to the MM patients, which may introduce variability in plantar pressure distribution. Future research should examine the difference in plantar pressure distribution when participants walk at the same speed. Finally, the wearable plantar pressure system lacked direct sensors for the medial and lateral positions of the hindfoot. Future studies should employ additional sensors at the medial/lateral hindfoot to further enhance the precision of knee alignment-related plantar pressure assessments.

Conclusions

MM patients with varus alignment exhibited reduced plantar pressure in both the posterior heel and the first phalanx during walking. During single-leg standing, the plantar pressure distribution in MM patients shifted laterally, and in those with varus alignment MM, the plantar pressure distribution also shifted forward. Moreover, the mediolateral stability of MM patients was diminished compared to healthy individuals. Attention should be paid to the changes in postural control following meniscus injury, with consideration of the influence of lower limb alignment, to design alignment-specific rehabilitation strategies aimed at improving stability and preventing long-term joint degeneration.

Abbreviations

MM	Medial meniscus
KOA	Knee osteoarthritis
HKA	Hip-knee-ankle angle
SLS	Single-leg stance
TFA	Tibiofemoral angle
T1 region	The first phalanx
M1 region	First metatarsal
M3 region	Third metatarsal
M5 region	Fifth metatarsal
MM region	Medial midfoot
ML region	Lateral midfoot
HA region	Anterior heel
HP region	Posterior heel
COP	Center-of-pressure
COPV	Center-of-pressure velocity
TTB	Time-to-boundary
ML	Medial-lateral
AP	Anterior-posterior

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None.

Author contributions
DJ and TZdesigned the study. The first draft of the manuscript was written by TZ. DJ reviewed and revised the manuscript. Material preparation was performed by RG and X.M.Wu. Data collection was performed by TZ and F.Y. Ding. RC and H.Y. Kang performed the statistical analysis. All authors read and approved the final manuscript and analysis.

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Data availability
Data is provided within the manuscript.

Declarations

Ethics approval and consent to participate
This work was approved by the Medical Ethics Committee of Peking University Third Hospital (M2024712) and all participants agreed and signed the informed consent. Informed consent was obtained from all individual participants included in the study.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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