ORIGINAL ARTICLE

Vibrating Perception Threshold and Body Mass Index Are Associated with Abnormal Foot Plantar Pressure in Type 2 Diabetes Outpatients

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Abstract

Aims: This study investigated the influencing factors of foot plantar pressure and attempted to find practical indicators to predict abnormal foot pressure in patients with type 2 diabetes mellitus (T2DM).

Subjects and Methods: Vibration perception threshold (VPT) and foot plantar pressure in 1,126 T2DM outpatients were examined. Patients were assigned to Group A ($n=599$), Group B ($n=312$), and Group C ($n=215$) according to VPT values and to Group I ($n=555$), Group II ($n=436$), and Group III ($n=135$) based on body mass index (BMI). The clinical characteristics and pressure-time integral (PTI) were compared among the three groups, and the associated factors of the total PTI in the entire foot (T-PTI) were analyzed.

Results: PTI of Group C in heel medial and heel lateral was significantly higher than that of Group A (all $P<0.01$). PTI of Group B in the right fifth metatarsal and heel medial was significantly higher than that of Group A (all $P<0.05$). T-PTI of Group C was significantly higher than those of Groups A and B, and that of Group B was higher than that of Group A (all $P<0.01$). PTI of Groups II and III in the second, third, and fourth metatarsal, midfoot, heel medial, and heel lateral was significantly higher than that of Group I (all $P<0.05$). T-PTI of Groups II and III was significantly higher than that of Group I (all $P<0.01$). Pearson correlation analysis showed that T-PTI was positively associated with age, VPT, waist circumference, waist-to-hip ratio, and BMI ($P<0.05$). In multiple stepwise regression analysis, VPT ($P=0.004$) and BMI ($P=0.000$) were independent risk factors of T-PTI, and each 1 unit increase in BMI increased the T-PTI by 5.962 kPa·s. Receiver operator characteristic curve analysis further revealed that the optimal cutpoint of VPT and BMI to predict the abnormal PTI was 21 V (odds ratio=2.33, 95% confidence interval 1.67–3.25) and 24.9 kg/m² (odds ratio=2.12, 95% confidence interval 1.55–2.90), respectively.

Conclusions: Having a VPT higher than 21 V and a BMI above 24.9 kg/m² increases the risk of excessive foot plantar pressure in Chinese T2DM.

Introduction

DIABETIC PERIPHERAL NEUROPATHY (DPN) is one of the most frequent complications of diabetes mellitus. Patients with DPN are at risk of ulceration on the sole of the foot. Foot ulcer is the leading cause of nontraumatic lower extremity amputation, which greatly impairs the quality of patients' lives. Studies have shown that high plantar pressure is associated with the ulceration in diabetes patients with peripheral neuropathy.^{1–3} Offloading devices are effective for healing of diabetic ulcers or preventing ulcers in the area at risk.⁴ A few studies have demonstrated that patients

with peripheral neuropathy have abnormal foot pressure.^{5–7} Elevated plantar pressures increase with peripheral neuropathy and degree of symptoms.⁷

It is well known that vibration perception threshold (VPT) is an inexpensive and convenient screening instrument reflecting perceptual peripheral neuropathy. A high VPT has been reported to be an independent predictor of foot ulceration.^{8,9} In contrast, there is little information available about the relationship between VPT and foot plantar pressure. So far, some research studies in Western countries have revealed that plantar pressure is increased in obese adults whose body mass index (BMI) was >30 kg/m².^{10–12}

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However, it is not clear whether BMI could influence foot pressure in the Chinese diabetes population and whether the BMI cutoff was concordant with a white population. In order to clarify whether VPT and BMI could be considered as sensitive risk indicators for abnormal foot plantar pressure, we compared the pressure-time integral (PTI) in patients with type 2 diabetes mellitus (T2DM) among three groups with different VPT and BMI in the present study.

Subjects and Methods

Subjects

In total, 1,126 T2DM outpatients were recruited from the Shanghai Clinical Medical Center of Diabetes. They were diagnosed as having T2DM based on 1999 World Health Organization criteria and American Diabetes Association standards. Patients with the following conditions were excluded: (a) lumbar intervertebral disc herniation, lumbar vertebral tumors, or other secondary lower extremity neuropathy; (b) lower limb osteoarthritis; (c) history of cerebral infarction and remained walking disability; (d) active plantar ulcer; (e) severe chronic diabetes complications such as retinopathy-related blindness, end-stage renal disease, and amputation; (f) poor glycemic control or acute complications of diabetes; or (g) history of stress such as fever, infection, or trauma in the past 2 weeks. The study was approved by the Ethics Committee of the Shanghai Sixth People's Hospital. Written informed consents were obtained from all participants.

Procedures

All patients' sex, age, BMI, waist circumference, waist-to-hip ratio, systolic blood pressure, diastolic blood pressure, symptom of limb extremity, duration of diabetes, and duration of positive lower extremity symptoms were recorded. BMI was calculated as body weight (in kg) divided by the square of the height (in m). The history of smoking, alcohol intake, coronary artery disease, hypertension, hyperlipidemia, cerebral apoplexy, nonalcoholic fatty liver disease, and (lower extremity) peripheral arterial disease was also collected.

The analysis of serum biochemical indexes, including blood urea nitrogen, serum creatinine, uric acid, total cholesterol, triglyceride, high-density lipoprotein cholesterol, low-density lipoprotein cholesterol, alanine aminotransferase, aspartate aminotransferase, and γ -glutamyl transpeptidase levels, was performed by enzymatic method with an automatic biochemical analyzer (Hitachi Inc., Tokyo, Japan). Fasting plasma glucose and 2-h postprandial blood glucose were measured by the glucose oxidase method. Glycosylated hemoglobin was estimated by high-pressure liquid chromatography using the Variant™ II machine (Bio-Rad Inc., Hercules, CA). Glycosylated serum protein was determined by the liquid enzymatic method using the Glamour 2000 automatic biochemical analyzer (MD Inc., Silicon Valley, CA).

VPT was measured by the same technician using a neurothesiometer (Bio-Thesiometer; Bio-Medical Instrument Co., Newbury, OH). The operational approaches were based on the International Working Group on the Diabetic Foot of the International Diabetes Federation.¹³ In brief, the subjects lay down, in a quiet and relaxed setting, in the decubitus position with eyes closed. The vibration probe was applied on a bony part on the dorsal side of the distal phalanx of the first toe. The

voltage (in V) was slowly increased in increments of 5 V, and the VPT, defined as the moment when the subject indicated he or she first felt the vibration, was recorded. The test was repeated three times, and the mean voltage was calculated and considered as the VPT result of this lateral. The higher value of VPT in either limb was used for analysis. As a general criterion, VPT was stratified as abnormal (VPT > 25 V), intermediate (VPT 16–25 V), and normal (VPT < 15 V).⁸ According to VPT results, patients were divided into three groups: Group A (VPT < 15 V), Group B (VPT 16–25 V), and Group C (VPT > 25 V). Also, the foot pressures in patients with different BMI values, including Group I ($\leq 25 \text{ kg/m}^2$), Group II ($25.1\text{--}27.9 \text{ kg/m}^2$), and Group III ($\geq 28 \text{ kg/m}^2$) were compared.

The ankle-brachial index (ABI), the ratio of ankle systolic pressure to arm systolic pressure, was detected according to the standard protocols recommended by the International Diabetes Federation.¹³ The lower value of ABI in either limb was used for analysis.

Dynamic plantar pressures were measured and recorded in the process of the subjects walking barefoot on the platform using the Footscan® force-plate system (RSscan Inc., Olen, Belgium). There were nine regions examined: great toe, metatarsal head 1–5, midfoot, heel medial (HM), and heel lateral (HL). The PTI of these nine regions and the total PTI of the entire foot (T-PTI) were calculated and analyzed. PTI reflects the cumulative effect of pressure over a certain period of time acting on the plantar.¹⁴ The normal range of T-PTI in Chinese subjects was $206 \pm 45 \text{ kPa}\cdot\text{s}$ as reported by Yan et al.¹⁵ In 1,022 healthy subjects. Thus T-PTI higher than $296 \text{ kPa}\cdot\text{s}$ (mean + 2 SD) was regarded as abnormal foot plantar pressure in this study.

Data analysis

Categorical variables were expressed as percentages, and continuous variables were given as mean $\pm$ SD values. Comparison of continuous variables among the three groups was performed by the Kruskal–Wallis test. The χ^2 test was used to assess differences for categorical variables. Associations between T-PTI and other variables were evaluated with Pearson correlation and multiple stepwise regression analysis. The receiver operating characteristic curve was carried out to find the cutoff of VPT and BMI to predict excessive foot pressure. Furthermore, the odds ratio value of VPT and BMI for forecasting abnormal plantar force was calculated by the χ^2 test. Statistical analyses were performed using SPSS version 16.0 software (SPSS Inc., Chicago, IL were expressed). $P < 0.05$ was considered statistically significant.

Results

Clinical characteristics

The clinical characteristics among the three groups are summarized in Table 1. There were significant differences in age, duration of diabetes, duration of positive lower extremity symptoms, VPT, ABI, percentage of coronary artery disease, percentage of lower extremity arterial disease, waist circumference, waist-to-hip ratio, systolic blood pressure, glycosylated hemoglobin, glycosylated serum protein, 2-h postprandial blood glucose, and blood urea nitrogen among the three groups (all $P < 0.05$). The age, duration of diabetes, duration of positive lower extremity symptoms, VPT, ABI,

TABLE 1. COMPARISON OF CLINICAL CHARACTERISTICS AMONG THE THREE VIBRATION PERCEPTION THRESHOLD GROUPS

	Group A	Group B	Group C	P
Patients (n)	599	312	215	—
Sex (M/F)	274/325	156/156	121/94	—
Age (years)	58.29 ± 11.47	64.94 ± 10.26 ^a	68.95 ± 10.10 ^{ac}	0.000
DM duration (years)	6.79 ± 6.19	8.73 ± 6.76 ^a	11.59 ± 7.47 ^{ac}	0.000
Duration of positive lower extremity symptoms (months)	7.99 ± 20.24	14.96 ± 23.78 ^a	15.14 ± 23.84 ^a	0.000
VPT (V)	11.61 ± 2.72	19.65 ± 2.67 ^a	36.66 ± 8.84 ^{ac}	0.000
ABI	1.05 ± 0.13	1.01 ± 0.17 ^a	0.95 ± 0.24 ^a	0.000
Percentage				
Smokers	18.06	22.93	23.70	0.197
Alcohol intake	12.64	9.69	12.70	0.577
CAD	8.55	9.28	19.51 ^{ac}	0.005
Hypertension	25.26	27.50	34.55	0.207
Hyperlipidemia	9.52	7.91	12.82	0.371
Cerebral apoplexy	5.90	10.55 ^b	10.94	0.063
Fatty liver	22.25	15.46	15.57	0.078
Lower extremity arterial disease	6.45	15.87 ^a	19.83 ^a	0.000
WC (cm)	87.20 ± 9.82	88.40 ± 9.77	90.27 ± 10.03 ^a	0.009
WHR	0.90 ± 0.07	0.92 ± 0.08 ^b	0.92 ± 0.07 ^b	0.018
BMI (kg/m ²)	24.18 ± 3.26	24.18 ± 3.18	24.27 ± 3.55	0.998
SBP (mm Hg)	127.89 ± 15.26	132.04 ± 16.75 ^a	134.23 ± 15.1 ^a	0.000
DBP (mm Hg)	78.50 ± 8.70	78.68 ± 9.56	78.72 ± 13.20	0.859
HbA1c (%)	7.62 ± 1.77	7.92 ± 1.82 ^b	8.31 ± 2.06 ^a	0.000
GA (%)	20.41 ± 5.69	21.59 ± 5.79 ^a	22.60 ± 6.13 ^a	0.000
FPG (mmol/L)	7.76 ± 2.55	7.85 ± 2.58	8.08 ± 2.88	0.457
PPG (mmol/L)	11.20 ± 3.83	11.44 ± 3.94	12.49 ± 4.92 ^a	0.034
BUN (mmol/L)	5.68 ± 2.21	5.27 ± 1.61	6.26 ± 2.68 ^c	0.004
Cr (μmol/L)	70.64 ± 42.48	71.14 ± 31.69	76.34 ± 36.71 ^b	0.119
UA (μmol/L)	312.52 ± 88.91	308.08 ± 84.80	313.50 ± 89.14	0.612
TC (mmol/L)	4.95 ± 1.19	5.01 ± 1.20	4.64 ± 0.90	0.120
TG (mmol/L)	1.77 ± 1.12	1.68 ± 0.95	1.74 ± 0.98	0.700
HDL-C (mmol/L)	1.27 ± 0.35	1.26 ± 0.34	1.23 ± 0.33	0.779
LDL-C (mmol/L)	3.21 ± 0.89	3.31 ± 1.02	3.07 ± 0.83	0.333
ALT (U/L)	24.89 ± 16.56	20.26 ± 12.25	21.15 ± 15.09	0.071
AST (U/L)	23.24 ± 12.17	21.48 ± 9.84	23.48 ± 20.07	0.318
GGT (U/L)	31.87 ± 30.57	23.92 ± 14.39	22.53 ± 16.92	0.054

Data are mean ± SD values.

^a*P* < 0.01, ^b*P* < 0.05, compared with Group A; ^c*P* < 0.01, compared with Group B.

ABI, ankle-brachial index; ALT, alanine aminotransferase; AST, aspartate aminotransferase; BMI, body mass index; BUN, blood urea nitrogen; CAD, coronary artery disease; Cr, serum creatinine; DBP, diastolic blood pressure; DM duration, diabetes mellitus duration; FPG, fasting plasma glucose; GA, glycosylated serum protein; GGT, γ -glutamyl transpeptidase; HbA1c, glycosylated hemoglobin; HDL-C, high-density lipoprotein cholesterol; LDL-C, low-density lipoprotein cholesterol; PPG, 2-h postprandial blood glucose; SBP, systolic blood pressure; TC, total cholesterol; TG, triglyceride; UA, uric acid; VPT, vibration perception threshold; WC, waist circumference; WHR, waist-to-hip ratio.

percentage of peripheral arterial disease, waist-to-hip ratio, systolic blood pressure, glycosylated hemoglobin, and glycosylated serum protein in Groups B and C were significantly higher than those in Group A (all *P* < 0.05). The age, duration of diabetes, VPT, and percentage of coronary artery disease in Group C were significantly higher than those in Group A (all *P* < 0.05).

PTI in each region of VPT subgroups

The PTI of the left and right foot is shown in Table 2. PTI of Group C in HM and HL was significantly higher than that of Group A (all *P* < 0.01). PTI of Group B in the right fifth metatarsal and HM was significantly higher than that of Group A (all *P* < 0.05). PTI in each region of Group C was higher compared with Groups A and B (*P* > 0.05), and PTI of

Group B in other region was slightly higher compared with Group A but without significance (*P* > 0.05). T-PTI of Group C was significantly higher than that of Group A and B, and that of Group B was higher than that of Group A (all *P* < 0.01).

Factors associated with T-PTI of the entire foot

The Pearson correlation analysis showed that T-PTI was positively associated with age, VPT, waist circumference, waist-to-hip ratio, and BMI (all *P* < 0.05) (Table 3). Taking T-PTI as the dependent variable, the variables, including age, VPT, waist circumference, waist-to-hip ratio, BMI, etc., were put into the stepwise multiple regression analysis. The results revealed that VPT (β = 0.120, *P* = 0.004) and BMI (β = 0.191, *P* = 0.000) were independent risk factors of T-PTI. By receiver operating characteristic analysis, the suitable cutpoint of VPT

TABLE 2. COMPARISON OF PLANTAR PRESSURE-TIME INTEGRAL AMONG THE THREE VIBRATION PERCEPTION THRESHOLD GROUPS

Region	Group A (n=599)		Group B (n=312)		Group C (n=215)	
	Left	Right	Left	Right	Left	Right
T1	8.80±10.61	8.76±11.81	8.80±10.61	9.23±12.27	9.71±12.49	10.21±15.57
M1	8.63±10.86	8.97±11.89	8.63±10.86	9.93±12.53	9.73±12.36	9.39±13.44
M2	13.63±11.02	13.51±10.63	13.80±9.03	14.18±9.51	16.07±15.08	14.53±12.98
M3	13.96±9.77	12.20±8.60	13.89±9.00	12.68±8.62	16.56±14.27	13.62±12.65
M4	9.50±7.48	9.08±7.81	9.22±6.39	9.18±8.21	10.44±9.66	9.79±9.60
M5	9.95±10.63	8.47±9.20	10.43±10.08	10.16±11.16 ^b	13.86±18.94	11.03±13.54
MF	2.32±5.99	2.77±4.55	2.32±4.93	2.88±5.18	3.29±8.46 ^d	3.27±6.05
HM	12.58±10.82	14.99±10.80	12.96±9.17	16.44±11.72 ^b	17.03±16.59 ^{ad}	19.53±15.94 ^{ad}
HL	13.09±10.00	10.89±9.26	13.12±8.95	11.56±9.20	17.17±16.46 ^{ad}	14.34±13.94 ^a
T-PTI						
Lateral	92.47±54.15	89.62±52.68	94.84±42.02 ^a	96.35±47.37 ^a	113.86±76.18 ^{ac}	105.71±71.06 ^{ad}
Bilateral	182.09±102.39		191.33±82.59 ^a		219.57±132.12 ^{ac}	

Data are mean±SD values.

^a*P*<0.01, ^b*P*<0.05, compared with Group A; ^c*P*<0.01, ^d*P*<0.05, compared with Group B.

HL, heel lateral; HM, heel medial; M1–M5, metatarsal head 1–5, respectively; MF, midfoot; T1, great toe; T-PTI, total pressure-time integral.

in predicting abnormal T-PTI was 21 V. The Youden index at this level is 0.22; its sensitivity was 45%, and the specificity was 77% (Fig. 1). The χ^2 test showed that the odds ratio value of VPT higher than 21V is 2.33 (95% confidence interval 1.67–3.25; *P*=0.000) for abnormal plantar pressure.

Relationship analysis between BMI and T-PTI

Because BMI was an independent risk factor of T-PTI, the patients were further assigned into three groups according to their BMI. The PTI of the left and right foot in the three BMI subgroups is shown in Table 4. PTI of Groups II and III in the second, third, and fourth metatarsal, midfoot, HM, and HL was significantly higher than that of Group I (all *P*<0.05). T-PTI of Groups II and III was markedly higher than that of Group I (all *P*<0.01). In the stepwise multiple regression analysis, each 1 unit increase in BMI increased the T-PTI by 5.962 kPa·s. By receiver operator characteristic analysis, the suitable cutpoint of BMI in predicting abnormal T-PTI was 24.9 kg/m². The Youden index at this level is 0.19; its sensitivity was 54%, and the specificity was 65%. The χ^2 test further showed a 2.12 times likelihood of abnormal plantar pressure when BMI was greater than 24.9 kg/m² (odds ratio=2.12; 95% confidence interval 1.55–2.90; *P*=0.000).

Discussion

To investigate the possible connection of VPT and the foot plantar pressure, we assigned patients to three groups ac-

cording to their VPT values and found that the patients who had higher VPTs also had higher age, duration of diabetes, duration of positive symptoms of lower extremity, blood pressure, blood glucose, ischemia of the lower extremity, waist-to-hip ratio, and percentage of coronary artery disease. The plantar PTI in each region increased in those having higher VPTs, especially in the region of HM and HL. T-PTI positively correlated with VPT, age, waist circumference, waist-to-hip ratio, and BMI. However, after adjusting for other variables, we found that only VPT and BMI were independent risk factors of T-PTI. Furthermore, VPT higher than 21 V was the optimal cutpoint to predict excessive pressure. And, in those having BMI greater than 24.9 kg/m², foot pressure of several regions and the total pressure were abnormally higher. A 1 unit increase of BMI could lead to the elevating of T-PTI by 5.962 kPa·s, and the odds ratio value of BMI above 24.9 kg/m² was 2.12 for excessive plantar pressure.

It is well known that the excessive pressure is a risk factor of incidence of foot ulceration in diabetes patients with peripheral neuropathy.^{1–3} The possible mechanisms include the direct mechanical disruption of foot soft tissue, prolonged pressure over an area that causes local ischemia and tissue breakdown, and repetitive forces inducing inflammation and enzymatic autolysis.¹⁶

Some research studies have investigated the relationship between plantar pressure and DPN diagnosed by clinical manifestations such as symptoms and physical signs. In

TABLE 3. PEARSON CORRELATION ANALYSIS OF THE FACTORS INFLUENCING TOTAL PRESSURE-TIME INTEGRAL

	Age	DM duration	DPS	VPT	ABI	WC	WHR	BMI	SBP	DBP	HbA1c	GA
<i>r</i>	0.094	0.059	0.042	0.135	−0.014	0.187	0.113	0.150	0.022	0.035	0.002	0.008
<i>P</i>	0.002	0.056	0.267	0.000	0.637	0.000	0.007	0.000	0.519	0.320	0.948	0.823

ABI, ankle-brachial index; BMI, body mass index; DBP, diastolic blood pressure; DM, duration of diabetes; DPS, duration of positive lower extremity symptoms; GA, glycosylated serum protein; HbA1c, glycosylated hemoglobin; SBP, systolic blood pressure; VPT, vibration perception threshold; WC, waist circumference; WHR, waist-to-hip ratio.

FIG. 1. Receiver operating characteristic of vibration perception threshold cutoff for excessive plantar pressure. Area under the curve=0.620 ($P=0.000$); 95% confidence interval 0.5790–0.661; identified vibration perception threshold cutpoint=21 V; Youden index=0.22; sensitivity, 45%; specificity, 77%.

patients who had a history of foot ulceration or peripheral neuropathy, plantar pressure was higher than in the control group, and the rear foot load increased.⁵ In the present study, plantar pressure in every region increased with VPT values, and the excessive pressure of the rear foot was more significant. In addition, Caselli et al.⁷ found that, although plantar pressure was enhanced in patients with DPN, the ratio of forefoot and rear foot pressure was higher in diabetes patients with the complication of severe diabetic neuropathy, indicating imbalance in the plantar pressure distribution. This discrepancy may be due to a difference of the severity of the neuropathy in the lower extremities, small foot deformation

owing to a long-term individual habit of footwear, or a congenital difference in height of foot arches. Nevertheless, other unclear reasons may exist. Further studies need to be conducted to find the detailed explanation for it. The mechanism of peripheral neuropathy inducing increased pressure may be the comprehensive effect of sensory neuropathy, motor neuropathy, and autonomic neuropathy.^{17,18}

We know that VPT is a simple, inexpensive, and accurate screening instrument for the early discrimination of perceptual peripheral neuropathy. Perceptual neuropathy is the most common etiology of the diabetic foot, which frequently results in loss of protective sensation and insensitivity to increased foot pressure, small injury, and injury-relevant hurting sensation. This study focused on looking for a practical clinical instrument to herald the risk of foot problems as early as possible in diabetes populations. We found that VPT higher than 21 V can predict abnormal increase in foot pressure and gives 1.33 times the risk in excessive foot pressure. We cannot deny the fact that the predictive sensitivity of VPT for T-PTI was low; nevertheless, its specificity reached 77%. Therefore, VPT could be used as a convenient and valid screening tool to indicate abnormal plantar pressure.

It is interesting that we also found that BMI is an independent risk factor of pressure in the entire foot. And, in those having BMI greater than 25 kg/m², foot pressure of several regions was abnormally higher. The odds ratio value of BMI above 24.9 kg/m² was 2.12 for excessive plantar pressure, and T-PTI increased 5.962 kPa·s with each 1 unit enhancement of BMI. This result was concordant with the results reported in Western countries such as Italy. Some researchers had found that the foot pressure increased in obese adults whose BMI was >30 kg/m².^{10,11} Birtane et al.¹² also proved that Grade 1 obese subjects (BMI between 30 and 34.9 kg/m²) had higher total plantar force than the nonobese group, and BMI was positively correlated with total plantar force. However, it seems that our BMI cutpoint was much lower than that in the previously examined white population. This may be explained by the racial difference of body mass between Asians and Europeans. In Chinese, epidemic survey data indicated that people whose BMI was greater than 25 kg/m² had increased risk of metabolic syndrome owing to abdominal

TABLE 4. COMPARISON OF PLANTAR PRESSURE–TIME INTEGRAL AMONG THE THREE BODY MASS INDEX GROUPS

	Group I (n=555)		Group II (n=436)		Group III (n=135)	
	Left	Right	Left	Right	Left	Right
T1	8.40±10.36	7.83±10.33	10.32±12.53 ^b	9.00±11.45	8.32±9.17	10.44±14.08
M1	8.68±9.85	9.02±12.31	9.55±12.55	9.16±11.60	8.79±12.08	10.05±13.67
M2	13.12±10.93	13.10±10.79	14.71±11.41 ^a	14.39±10.94 ^a	16.26±12.47 ^a	15.03±9.75 ^a
M3	13.43±9.83	11.54±8.92	14.85±9.90 ^a	13.30±9.55 ^a	15.80±10.53 ^a	13.59±8.24 ^a
M4	8.99±7.74	8.14±6.73	9.83±7.47 ^b	10.08±9.47 ^a	10.60±7.22 ^a	10.22±7.95 ^a
M5	10.58±13.07	8.71±9.90	10.45±11.42	9.46±10.28	11.87±11.07 ^{bd}	9.94±11.38
MF	2.35±7.50	2.35±4.41	2.09±3.71 ^a	3.23±5.46 ^a	4.57±7.54 ^{ac}	4.31±6.73 ^a
HM	12.03±10.84	14.56±11.12	14.55±11.67 ^a	17.43±13.09 ^a	13.88±11.29 ^b	17.49±12.71 ^a
HL	12.54±10.14	10.42±9.43	14.62±10.68 ^a	12.62±10.84 ^a	14.73±10.25 ^a	12.59±10.56 ^a
T-PTI						
Lateral	90.11±51.62	85.68±49.86	100.96±56.35 ^a	98.76±54.04 ^a	104.82±55.55 ^a	103.64±57.41 ^a
Bilateral	175.79±95.03		199.58±102.85 ^a		209.25±102.83 ^a	

Data are mean±SD values.

^a $P<0.01$, ^b $P<0.05$, compared with Group I; ^c $P<0.01$, ^d $P<0.05$, compared with Group II.

HL, heel lateral; HM, heel medial; M1–M5, metatarsal head 1–5, respectively; MF, midfoot; T1, great toe; T-PTI, total pressure-time integral.

obesity.¹⁹ Consequently, BMI ≥ 25 kg/m² was considered as the diagnostic criterion for obesity in the Chinese population.²⁰ The BMI cutoff of the present study was very close to the above BMI standard. Thus BMI higher than 24.9 kg/m² may be adapted to forecast the risk of excessive plantar pressure and the diabetic foot in the Chinese diabetes population. On the other hand, we must address the fact that the BMI cutoff in the present study to predict the greater foot pressure was suitable only for Chinese Hans, and the related BMI value may be different in whites. Therefore, further studies are needed to explore the special cutpoint of BMI in other races. It is actually quite reasonable that obesity can augment much pressure on bilateral foot plantar. In consequence, decreasing BMI may reduce foot pressure; accordingly, weight reduction could be a potential approach to reduce the risk of foot ulceration in obese diabetes patients with peripheral neuropathy.

There are some limitations of the present study. First, the sample size was relatively small, especially the group with abnormal VPT and BMI, and it may affect the accuracy of these two indicators on abnormal foot pressure. Second, these subjects were old, and we could not exclude the impact of aging on the foot deformities and bone density, which may influence the T-PTI of the entire foot. Finally, this was a cross-sectional study, and we cannot provide the end point results of the incidence of foot ulceration in the different VPT and BMI subgroups. Thus, further follow-up of these patients should be carried out to verify the efficacy of amending VPT and BMI on the prevention of foot problems.

In summary, we found that VPT higher than 21 V resulted in 2.33 times greater likelihood and BMI greater than 24.9 kg/m² resulted in 2.12 times greater likelihood of abnormal plantar pressure. Consequently, screening and identifying VPT higher than 21 V and BMI greater than 24.9 kg/m² can be considered as practical instruments to predict the risk of elevated plantar pressure. Meanwhile, therapeutic insoles and footwear or other offloading devices should be provided to patients with abnormal VPT and plantar pressures. Moreover, because obesity is also a risk factor that contributes to higher diabetic foot forces and because a 1 unit increase in BMI means a 5.962 kPa·s rise in foot plantar pressure, it is important for diabetes patients with DPN to lose weight by diet control and more physical exercise to decrease the risk of foot ulceration.

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Author Disclosure Statement

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