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RESEARCH

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Weight-adjusted waist index is associated with risk of poor bone quality rather than low bone mass in patients with type 2 diabetes

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Abstract

Background Type 2 diabetes (T2D) correlates with an elevated risk of osteoporotic fractures. However, factors influencing bone mineral density (BMD) and trabecular bone score (TBS) in Chinese individuals with T2D remain unclear. This study aimed to investigate the clinical and biochemical determinants of BMD and TBS in patients with T2D, with a focus on elucidating the role of weight-adjusted waist index (WWI) in modulating bone mass and quality in this cohort.

Methods Data of 161 women and 153 men with T2D collected between July 2022 and March 2023 in Shenzhen, China, were analyzed in our cross-sectional study. Lumbar spine BMD and TBS of all participants were obtained using dual-energy X-ray absorptiometry. WWI was defined as waist circumference over the square root of weight.

Results Multivariate regression analysis demonstrated that lumbar spine TBS was inversely correlated with age, menopausal status, and WWI in women ($p < 0.05$). In men, TBS was negatively associated with age and WWI ($p < 0.05$). For women, glycated hemoglobin A1c positively influenced BMD ($p < 0.05$), whereas age, diabetic retinopathy, and N-mid osteocalcin were negatively associated. No significant predictors of BMD were identified in the male cohort. For predicting degraded TBS, the optimal WWI cut-offs were 11.257 cm/√kg (S: 61.1%, E: 80.7%) in males and 11.247 cm/√kg (S: 70.3%, E: 71.1%) in females.

Conclusions Our findings highlight WWI as a novel and potentially more precise indicator of body fat, associated with diminished bone quality rather than solely low bone mass in patients with T2D in China. These results suggest that evaluating bone health in individuals with higher WWI may require more than just bone mass assessment. The results also suggest that the optimal WWI cut-off points for predicting degraded TBS are approximately 11.25 cm/√kg, highlighting thresholds for fracture risk.

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Mini Abstract
Sex-specific factors influencing bone mass and quality in individuals with type 2 diabetes remain unclear. We found that the weight-adjusted waist index was associated with diminished bone quality rather than solely low bone mass in these individuals. This metric could be a tool for predicting fracture risk in this population.

Keywords Weight-adjusted waist index, Obese, Trabecular bone score, Type 2 diabetes, Bone fracture

Background

Type 2 diabetes (T2D) and its associated complications represent a significant global health burden, leading to markedly increased healthcare expenditures worldwide [1]. Based on the International Diabetes Federation research, roughly 537 million adults (aged 20 – 79 years) worldwide had diabetes mellitus in 2021 [2]. Recently, osteoporosis was recognized as a microvascular complication of diabetes, a condition now termed "diabetic bone disease," and has emerged as a critical area of research [3–6]. The most debilitating consequence of osteoporosis is fragility fractures, which can cause disability and even death. A large epidemiological survey indicates a significant incidence of osteoporosis and fragility fractures in China, with 5% of males and more than 20% of females over 40 years of age diagnosed with osteoporosis [7]. Additionally, vertebral fractures occur in more than 10% of males and approximately 9% of females over 40 years old [7]. Therefore, bone status should be precisely evaluated in patients with diabetes complicated by osteoporosis.

Bone mineral density (BMD) is a routine diagnostic criterion for osteoporosis and serves as a principal predictor of fracture risk [8]. Although individuals with T2D often demonstrate normal or increased BMD relative to controls without diabetes, they exhibit an increased susceptibility to fragility fractures [9]. Thus, reliance on BMD alone for assessing bone in patients with T2D is insufficient. A comprehensive assessment should incorporate BMD alongside other facets of bone quality, including microarchitectural integrity and material properties. The trabecular bone score (TBS), a new non-invasive imaging parameter, quantifies trabecular microarchitecture by analyzing grayscale texture diversities in dual-energy X-ray absorptiometry (DXA) visuals, which correlate with 3D bone features such as trabecular separation, connectivity density, and trabecular number [10, 11]. Higher TBS values are indicative of enhanced microstructural resilience against fractures. Studies have demonstrated that patients with T2D exhibit compromised trabecular microarchitecture compared to adults without diabetes of the same age [12, 13]. The increased or normal BMD found in individuals with T2D is inconsistent with an impaired bone microstructure, which cannot be underestimated in assessing bone health.

Obesity is a common complication of T2D and increases the risk of osteoporosis in these individuals [14, 15]. Typically, obesity is determined using metrics such as body weight, waist circumference (WC), and body mass index (BMI). Higher BMI positively affects bone health in individuals with T2D [16]. Conflicting evidence indicates an increased fracture risk among these individuals [17, 18]. Thus, BMI alone is insufficient to value fracture risk in patients with T2D. A new index called weight-adjusted waist index (WWI), defined as WC divided by the square root of body weight, has been introduced for assessing obesity [19]. The WWI is considered a more precise indicator of adiposity than WC or BMI alone [20]. Although WWI has been associated with bone mass in populations without diabetes [21], its relationship with bone health in patients with T2D remains unknown.

Furthermore, research indicates that osteoporosis is more prevalent among females than among males; however, the incidence of vertebral fractures is similar across both sexes [7]. Moreover, the influence of T2D on these patterns remains uncertain. In this study, we aimed to investigate the clinical and biochemical factors influencing TBS and BMD in patients with T2D. Specifically, we explored the impact of WWI on bone mass and quality in patients with T2D.

Methods

Study design and population

This cross-sectional study was performed at Shenzhen Second People's Hospital (the First Affiliated Hospital of Shenzhen University) from July 2022 to March 2023. Patients diagnosed with T2D, according to the American Diabetes Association guidelines, were recruited [21]. Exclusion criteria encompassed rheumatoid arthritis, chronic hepatic or renal disorders, active malignancy, hormone replacement therapy, history of fractures, prior diagnosis of osteoporosis, prior fragility fractures, pharmacotherapies for osteoporosis and prior glucocorticoid use.

The research protocol was approved by the Ethics Committee (2024-176-01PJ) of Shenzhen Second People's Hospital (the First Affiliated Hospital of Shenzhen University) and conformed with the principles of the Declaration of Helsinki. Written informed consent was obtained from all patients.

Data collection

Lumbar spine BMD (T-score) was assessed using DXA (GE Lunar iDXA; GE Healthcare, Madison, WI, USA),

and lumbar spine TBS was retrospectively calculated using TBS iNsight software (version 3.0.0, Medimaps, Switzerland). Height (m) and weight (kg) were measured following standardized protocols. BMI (kg/m2) was calculated as the weight divided by the square of the height. WC (cm) was measured using a standardized approach: the patient's feet were approximately 30 cm apart, and a nonelastic, soft measuring tape with a minimum scale of 1 mm was used to measure the midpoint of the line connecting the highest point of the iliac crest and the lower edge of the 12th rib in a horizontal direction. The tape was applied snugly around the abdomen without compressing the skin. WWI (cm/√kg) was calculated as the WC divided by the square root of body weight.

Data on participants' age, sex, smoking history, alcohol consumption, and menstrual history were obtained via structured questionnaires. Fasting venous blood specimens were collected in the morning to measure levels of 25-hydroxyvitamin D, serum calcium, glycated hemoglobin A1c (HbA1c), and lipid profiles (total cholesterol, low-density lipoprotein cholesterol, and triglycerides) using standard biochemical assays. N-mid osteocalcin, parathyroid hormone, procollagen type I N-terminal propeptide (P1NP), and c-terminal telopeptide of type I collagen were quantified using standard biochemical methods.

Statistical analysis

Continuous variables were presented as mean ± standard deviation. The Mann–Whitney U test was employed for non-normally distributed variables, while unpaired Student's t-test was applied to normally distributed continuous variables. For categorical variables, numbers and/or percentages were used for representation, and $\chi 2$ tests were conducted. Simple linear regression was initially conducted to examine the association between TBS, BMD, and factors influencing bone quality. Variables with a p value ≤ 0.2 in the simple linear regression were included in a multivariable linear regression model, adjusting for potential confounders to further assess their impact on bone quality. Degraded TBS was defined as TBS < 1.23 [22]. Receiver Operating Characteristic (ROC) analysis was performed to determine cut-off points for male and female patients. Statistical analyses were performed using IBM SPSS Statistics (version 25.0; IBM Corp., Armonk, NY, USA), with statistical significance set at $p < 0.05$ (two-tailed).

Results

Population characteristics

A total of 161 female (ages 33–87 years) and 153 male (ages 32–81 years) patients with T2D were enrolled in this study (Fig. 1 and 2).

Compared with male patients, female patients were significantly older ($p = 0.001$) and had higher WWI ($p = 0.001$) and N-mid osteocalcin levels ($p = 0.049$); however, their WC ($p < 0.001$), weight ($p < 0.001$), lumbar spine TBS ($p < 0.001$), metformin use ($p < 0.001$),femoral neck BMD T-score ($p < 0.001$), total hip BMD T-score ($p < 0.001$) and lumbar spine BMD T-score ($p < 0.001$) were lower. Other evaluated parameters were similar in both sexes (Table 1).

Predictors of lumbar spine TBS

In the simple linear regression analysis, among females, parathyroid hormone was positively correlated, whereas age, menopausal status, diabetic retinopathy, WC, and WWI exhibited inverse correlations with lumbar spine TBS. Among males, serum calcium exhibited a positive, whereas age, diabetes duration and WWI demonstrated a negative association with lumbar spine TBS, similar to the findings in female patients (Table 2).

In the multivariable regression analyses, among women, lumbar spine TBS was negatively influenced by age (B = −0.002, $p = 0.019$), menopausal status (B = −0.086, $p = 0.004$), and WWI (B = −0.026, $p = 0.004$) (Table 3). Similarly, in male patients, age (B = −0.001, $p = 0.050$) and WWI (B = −0.043 $p = 0.001$) were identified as negative predictors of lumbar spine TBS (Table 4). Menopausal history did not significantly alter the inverse relationship between WWI and TBS (not shown).

Predictors of lumbar spine BMD

In the simple correlation analysis (Table 5), HbA1c and BMI were positively associated with lumbar spine BMD in females, whereas age, menopausal status, WWI, and N-mid osteocalcin were inversely correlated. Notably, no significant correlations with BMD were found in males with T2D.

To further delineate independent variables affecting BMD, a multiple stepwise linear regression analysis was conducted for both groups (Table 6). In women, HbA1c (B = 0.199, $p = 0.001$) positively influenced BMD, whereas age (B = −0.042, $p < 0.001$), diabetic retinopathy (B = −0.264, $p = 0.033$), and N-mid osteocalcin (B = −0.028, $p = 0.038$) were negative predictors of BMD T-score (Table 6). Consistent with previous findings, no significant variables were retained in the final model for male patients.

Predictor of degraded TBS

In ROC analysis (Table 7), the optimal cut-off points were explored by examining the sensitivity and 1-specificity for patients with degraded TBS. The total area under the curve (AUC) was 0.686 (95% CI: 0.529–0.842) for males and 0.715 (95% CI: 0.631–0.798) for females. The optimal

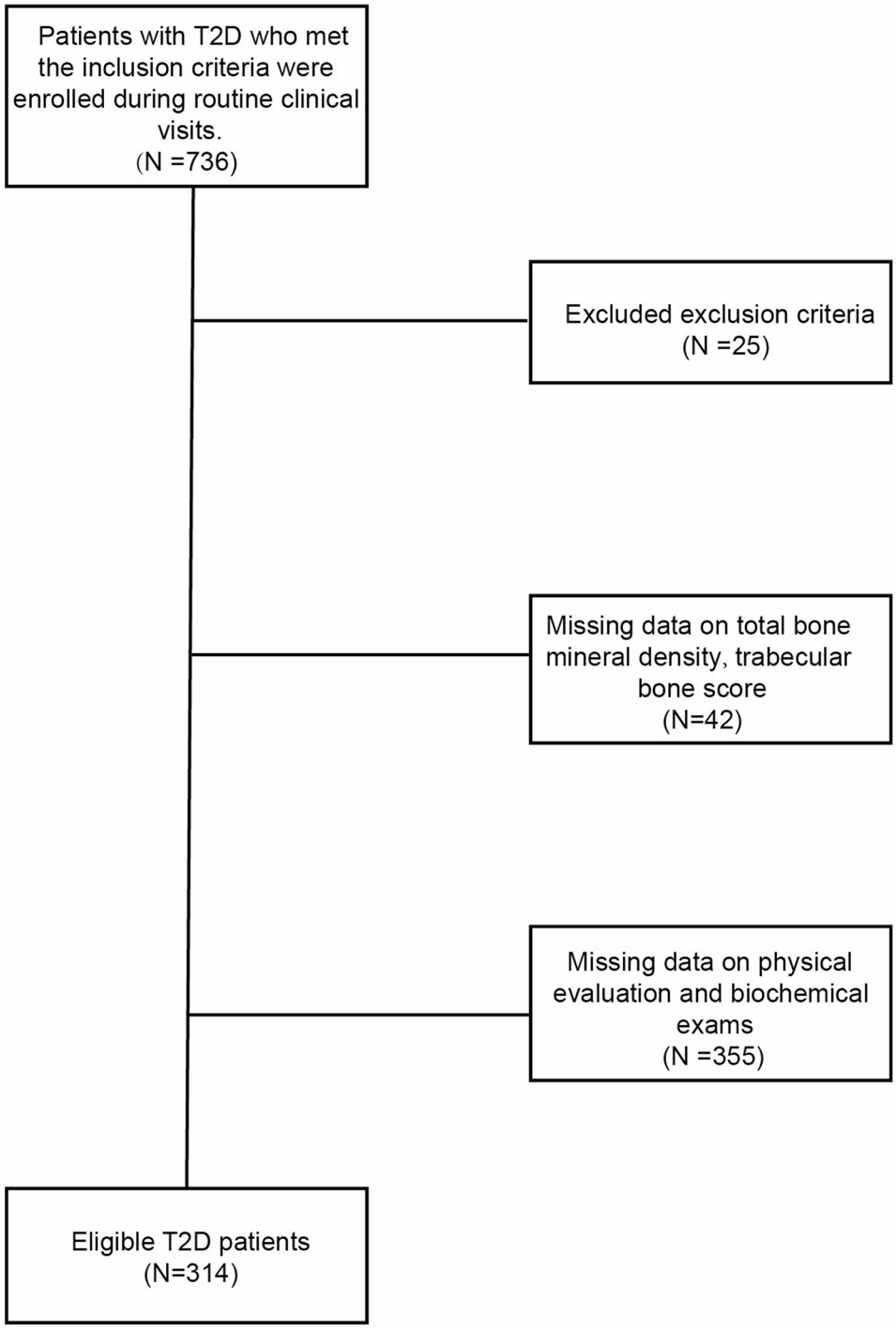

Fig. 1 Flow diagram of recruitment

WWI cutoff values were determined as 11.257 cm/√kg for males and 11.247 cm/√kg for females.

Discussion

In this study, female patients with T2D exhibited lower lumbar spine TBS and BMD compared with male patients. Common predictors of TBS across both sexes were WWI and age. In women with T2D, menopause emerged as an independent predictor of TBS. The primary determinants of BMD in female patients with T2D were age, HbA1c, N-mid osteocalcinand diabetic retinopathy. Interestingly, no independent predictors were identified for BMD in males with T2D.

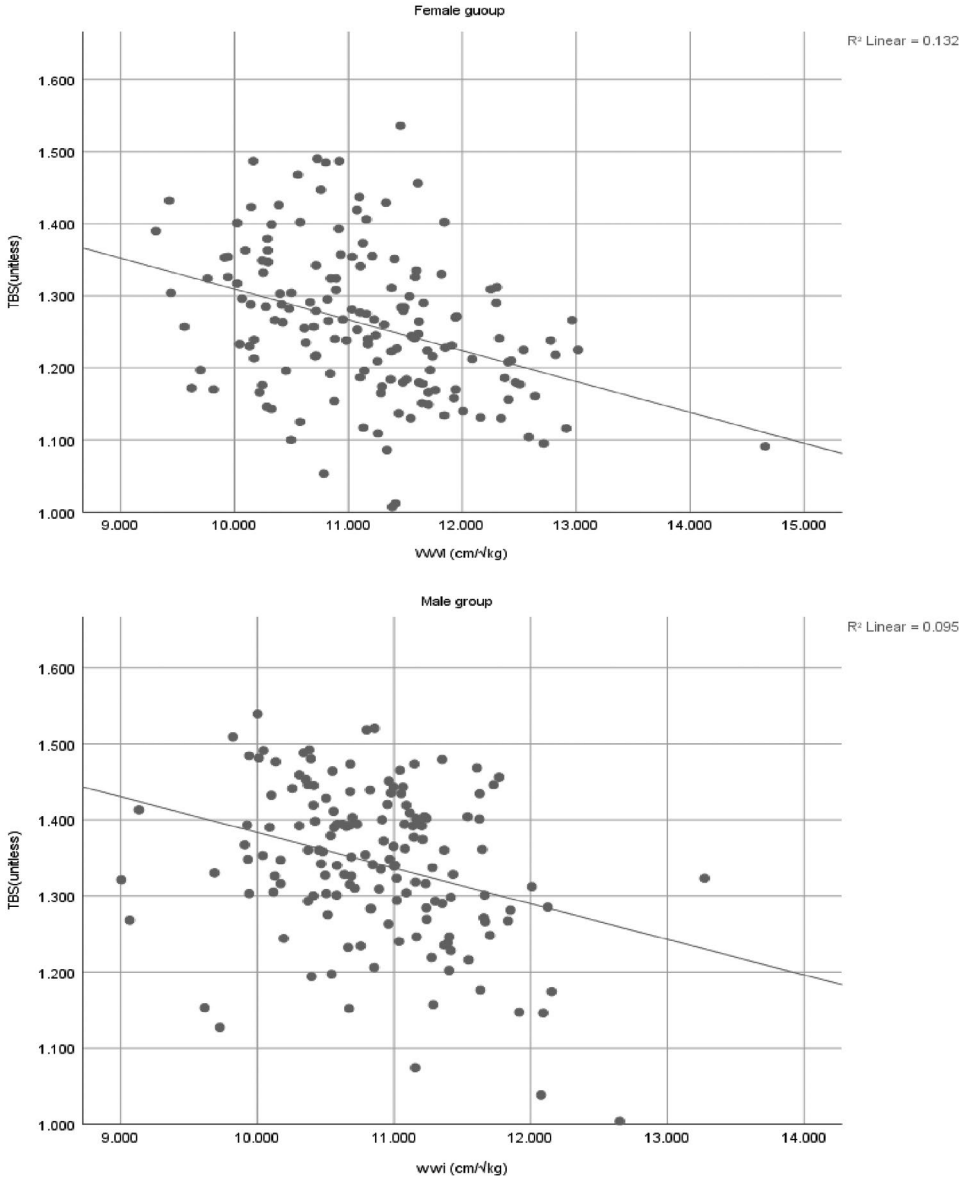

Fig. 2 Scatterplots between weight-adjusted waist index (WWI) and trabecular bone score (TBS) in the female and male groups

The TBS and BMD serve as distinct indicators for assessing fracture risk, offering complementary insights when considered together. While BMD is widely used to assess bone health, it cannot comprehensively predict fracture risk in individuals with T2D. Notably, existing literature describes a paradoxical scenario where some patients with T2D exhibit an elevated osteoporotic fracture risk despite normal BMD [9, 23, 24]. Conversely, TBS, which evaluates bone microarchitecture, has shown a significant inverse correlation with osteoporotic fracture risk in patients with T2D [23, 25, 26]. While numerous studies have examined the relationship between TBS and its determinants in this population, most have not differentiated between sexes, leaving a gap in understanding sex-specific factors influencing TBS in patients with T2D.

Previous studies have investigated the influence of obesity on bone metabolism, particularly the relationship between WC, BMI, and fracture risk. However, the results have been inconsistent. De Laet et al. reported that BMI-defined obesity had a prophylactic effect against bone mass loss and vertebral fractures, while WC-based obesity was a potential risk factor for osteoporosis [27–29]. In our study, in the simple linear regression model, WC was a risk factor for decreased TBS in female patients with T2D, whereas BMI was not associated with TBS in either sex. In the multiple linear regression models, neither BMI nor WC correlated with the TBS in either sex. BMI, the most commonly used measure

Table 1 Demographic and clinical characteristics of patients with T2D based on sex

Variable	Female (*N* = 161)	Male (*N* = 153)	*p* values
Age (years)	62.610 ± 9.850	58.720 ± 11.435	0.001*
Diabetes duration	11.723 ± 7.774	10.428 ± 7.593	0.137
Menopause history (%)			
no	19 (11.80%)		
yes	142 (88.20%)		
Smoking history (%)			
no	161 (100.00%)	61 (39.87%)	
yes	0 (0.00%)	92 (60.13%)	
Drinking history (%)			
no	160 (99.38%)	90 (58.82%)	
yes	1 (0.62%)	63 (41.18%)	
Weight (kg)	59.900 ± 10.730	71.255 ± 11.902	< 0.001*
BMI (kg/m2)	24.353 ± 4.263	25.342 ± 8.559	0.193
WC (cm)	85.982 ± 9.876	91.395 ± 9.422	< 0.001*
WWI (cm/√kg)	11.155 ± 0.866	10.860 ± 0.657	0.001*
HbA1c (%)	8.560 ± 1.981	8.822 ± 2.359	0.288
TG (mmol/L)	1.841 ± 1.699	1.870 ± 1.568	0.872
TC (mmol/L)	4.500 ± 1.439	4.252 ± 1.123	0.091
LDL-C (mmol/L)	2.834 ± 1.209	2.705 ± 0.946	0.291
Ca (mmol/L)	2.251 ± 0.136	2.248 ± 0.217	0.889
25-(OH)VitD (ng/mL)	24.689 ± 8.423	25.320 ± 8.150	0.501
PTH(pg/mL)	33.456 ± 21.797	32.342 ± 18.729	0.628
N-mid osteocalcin (ng/mL)	15.850 ± 8.001	14.337 ± 4.556	0.042*
P1NP (ng/mL)	38.490 ± 19.597	35.635 ± 17.442	0.174
β-CTX (ng/mL)	0.413 ± 1.039	0.321 ± 0.241	0.288
Metformin Use (%)			< 0.001*
no	97 (63.4%)	67 (41.6%)	
yes	56 (36.6%)	94 (58.4%)	
Diabetic Retinopathy			0.437
no	100 (65.4%)	99 (61.5%)	
yes	53 (34.6%)	62 (38.5%)	
Diabetic Nephropathy			0.377
no	93 (60.8%)	112 (69.6%)	
yes	60 (39.2%)	50 (30.4%)	
Diabetic Peripheral Neuropathy			0.748
no	66 (43.1%)	67 (41.6%)	
yes	86 (56.9%)	94 (58.4%)	
Lumbar spine TBS	1.260 ± 0.102	1.343 ± 0.100	< 0.001*
Lumbar spine BMD T-score	-1.322 ± 1.486	-0.389 ± 1.465	< 0.001*
Femoral neck BMD T-score	-1.777 ± 0.937	-1.183 ± 0.945	< 0.001*
Total hip BMD T-score	-1.084 ± 1.128	-0.509 ± 1.046	< 0.001*

Data for continuous variables are presented as the mean ± SD

*Level of significance: $p < 0.05$. The unpaired t-test or Mann–Whitney's test were used for comparisons of the quantitative variables between female and male groups

Abbreviations: BMI: body mass index; WC: waist circumference; WWI: weight-adjusted waist index; HbA1c: glycated hemoglobin A1c; TG: triglycerides; TC: total cholesterol; LDL-C: low-density lipoprotein cholesterol; Ca: serum calcium; 25-(OH)VitD: 25-hydroxyvitamin D; PTH: parathyroid hormone; P1NP: procollagen type 1 N-terminal propeptide; β-CTX: c-terminal crosslaps of type 1 collagen; TBS: trabecular bone score; BMD: bone mineral density; SD, standard deviation

Table 2 Simple correlation analysis between different variables and TBS in the female and male groups

Variables	Female group		Male group	
	r	*p* values	*r*	*p* values
Age (years)	-0.473	< 0.001*	-0.266	0.001*
Menopause history	-0.447	< 0.001*		
Smoking history			-0.078	0.336
Drinking history	0.065	0.411	-0.111	0.174
WWI (cm/√kg)	-0.364	< 0.001*	-0.308	< 0.001*
BMI (kg/m^2)	-0.036	0.655	-0.065	0.426
WC (cm)	-0.205	0.009*	-0.129	0.111
HbA1c (%)	0.058	0.469	-0.029	0.718
TG (mmol/L)	-0.091	0.254	-0.047	0.562
TC (mmol/L)	0.038	0.633	0.037	0.653
LDL-C (mmol/L)	0.073	0.357	0.042	0.608
Ca (mmol/L)	0.001	0.991	0.165	0.041*
25-(OH)VitD (ng/mL)	-0.008	0.920	0.081	0.318
PTH(pg/mL)	0.190	0.016*	-0.084	0.304
N-mid osteocalcin (ng/mL)	-0.092	0.245	-0.081	0.317
P1NP (ng/mL)	-0.042	0.596	-0.125	0.123
β-CTX (ng/mL)	-0.044	0.576	-0.018	0.827
Metformin Use	-0.055	0.484	0.097	0.231
Diabetes duration	-0.106	0.184	-0.165	0.041*
Diabetic Retinopathy	-0.173	0.035*	0.011	0.898
Diabetic Nephropathy	-0.106	0.204	-0.145	0.097
Diabetic Peripheral Neuropathy	-0.111	0.163	-0.115	0.158

*Level of significance: $p < 0.05$

Abbreviations: BMI: body mass index; WC: waist circumference; WWI: weight-adjusted waist index; HbA1c: glycated hemoglobin A1c; TG: triglycerides; TC: total cholesterol; LDL-C: low-density lipoprotein cholesterol; Ca: Serum calcium; 25-(OH)VitD: 25-hydroxyvitamin D; PTH: parathyroid hormone; TBS: trabecular bone score; BMD: bone mineral density; P1NP: procollagen type 1 N-terminal propeptide; β-CTX: c-terminal crosslaps of type 1 collagen. Scatter plots illustrated a significant negative correlation between WWI and lumbar spine TBS in both female ($r = -0.364$, $p < 0.001$) and male patients ($r = -0.308$, $p < 0.001$), as shown in Fig. 2

of obesity in clinical settings, cannot effectively estimate body fat percentage, particularly in individuals with a higher BMI, where it does not accurately predict bone density compared with weight [30]. Although more precise methods are available to determine the total body fat percentage, these techniques are considered impractical for clinical use. WWI has emerged as a novel indicator of body fat that is easy to measure and provides insights into fat accumulation and muscle content within the body [19]. Subsequently, ROC analysis revealed a cut-off point of approximately 11.25 cm/√kg for both male and female groups. Notably, AUC for the female cohort exceeded 0.7, while that for males was below 0.7, indicating superior predictive accuracy in females compared to males. Based on these findings, we propose 11.25 cm/√kg as a clinically applicable threshold for predicting degraded TBS in individuals with T2DM.

Prior research primarily focused on the association between WWI and BMD, with several studies indicating that elevated WWI was associated with bone loss,

Table 3 Multiple regression analysis for predictors of TBS in the female group

	Non-standardized coefficients		Typified coefficients			
	B	Error Typ.	β	t	95% CI	*p* Value
TBS						
Age	-0.002	0.001	-0.219	-2. 378	-0.004 to -0.001	0.019
Menopause history	-0.086	0.029	-0.253	-2.929	-0.144 to -0.028	0.004
WWI	-0.026	0.009	-0.221	-2.901	-0.043 to -0.008	0.004

Abbreviations: WWI: weight-adjusted waist index; TBS: trabecular bone score; CI: confidence interval

Note: Variables included in the original model were: age, menopause history, WWI, diabetes duration, diabetic retinopathy, diabetic peripheral neuropathy, waist circumference, and parathyroid hormone

Table 4 Multiple regression analysis for predictors of TBS in the male group

	Non-standardized coefficients		Typified coefficients			
	B	Error Typ.	β	t	95% CI	*p* Value
TBS						
Age	-0.001	0.001	-0. 167	-1.979	-0.003 to 0.000	0.050
WWI	-0.043	0.012	-0.296	-3.505	-0.067 to -0.019	0.001

Abbreviations: WWI: weight-adjusted waist index; P1NP: procollagen type 1 N-terminal propeptide; TBS: trabecular bone score; CI: confidence interval

Note: Variables included in the original model were: age, drinking history, WWI, waist circumference, calcium level, diabetes duration, diabetic nephropathy, diabetic peripheral neuropathy and P1NP

Table 5 Simple correlation analysis between different variables and BMD in the female and male groups

Variables	Females group		Males group	
	r	*p* values	*r*	*p* values
Age (years)	-0.344	< 0.001*	0.012	0.884
Menopause history	-0.338	< 0.001*		
Smoking history			-0.102	0.208
Drinking history	-0.006	0.941	< 0.001	0.997
WWI (cm/√kg)	-0.161	0.042*	-0.071	0.381
BMI (kg/m^2)	0.180	0.022*	-0.040	0.624
WC (cm)	0.115	0.146	0.120	0.140
HbA1c (%)	0.234	0.003*	-0.074	0.366
TG (mmol/L)	0.019	0.809	0.052	0.522
TC (mmol/L)	0.108	0.175	0.017	0.839
LDL-C (mmol/L)	0.148	0.060	-0.019	0.815
Ca (mmol/L)	-0.022	0.782	0.062	0.445
25-(OH)VitD (ng/mL)	0.024	0.766	-0.018	0.830
PTH(pg/mL)	-0.143	0.071	-0.033	0.683
N-mid osteocalcin (ng/mL)	-0.218	0.006*	-0.034	0.673
P1NP (ng/mL)	-0.149	0.060	-0.136	0.093
β-CTX (ng/mL)	-0.090	0.257	-0.141	0.082
Metformin Use	0.066	0.403	0.063	0.438
Diabetes duration	-0.091	0.254	0.092	0.256
Diabetic Retinopathy	-0.141	0.087	0.107	0.199
Diabetic Nephropathy	-0.042	0.619	-0095	0.280
Diabetic Peripheral Neuropathy	-0.052	0.513	-0.068	0.408

*Level of significance: $p < 0.05$. Abbreviations: BMI: body mass index; WC: waist circumference; WWI: weight-adjusted waist index; HbA1c: glycated hemoglobin A1c; TG: triglycerides; TC: total cholesterol; LDL-C: low-density lipoprotein cholesterol; Ca: serum calcium; 25-(OH)VitD: 25-hydroxyvitamin D; PTH: parathyroid hormone; TBS: trabecular bone score; BMD: bone mineral density; P1NP: procollagen type 1 N-terminal propeptide; β-CTX: c-terminal crosslaps of type 1 collagen

osteoporosis, and reduced BMD [19, 31, 32]. However, our study showed no significant correlation between WWI and BMD. Notably, WWI demonstrated a significant inverse relationship with TBS in both patient groups. The impact of WWI on bone metabolism is attributed to two primary factors: augmentation of fat levels and decline in muscle mass.

Excessive adiposity significantly heightens the risk of fractures. First, increased fat deposition leads to greater static mechanical compliance of the body, resulting in alterations in bone architecture due to modified static mechanical forces exerted on the skeletal system [33, 34]. Second, bone marrow mesenchymal stem cells can differentiate into both osteoblasts and adipocytes [35]. Obesity can drive the differentiation of bone marrow mesenchymal stem cells into adipocytes, thereby increasing the presence of adipocytes and reducing the number of osteoblasts within the bone marrow [36]. Third, excessive adipocyte accumulation triggers an inflammatory response, accelerating the release of proinflammatory and immunomodulatory mediators within the bone microenvironment. These inflammatory factors not only stimulate osteoclastogenesis but also inhibit osteoblast differentiation, leading to an imbalance in bone remodeling [37]. Finally, the accumulation of adipocytes enhances the synthesis and secretion of endocrine factors such as estrogen, insulin, and leptin, which, while generally inhibitory to bone resorption and bone remodeling processes, can contribute to dysregulated bone homeostasis in the context of obesity [38–40].

Table 6 Multiple regression analysis for predictors of BMD in the female group

	Non-standardized coefficients		Typified coefficients			
	B	Error Typ.	β	t	95% CI	*p* Value
BMD						
Age	-0.042	0.011	-0.284	-3.783	-0.064 to -0.020	< 0.001
HbA1c	0.199	0.058	0.266	3.448	0.085 to 0.314	0.001
N-mid osteocalcin	-0.028	0.014	-0.156	-2.089	-0.055 to -0.002	0.038
Diabetic Retinopathy	-0.264	0.123	0.167	-2.089	-0.506 to -0.022	0.038

Abbreviations: WWI: weight-adjusted waist index; HbA1c: glycated hemoglobin A1c; BMD: bone mineral density; BMI: body mass index; CI: confidence interval. Multiple stepwise models of linear regression analysis. Variables included in the original model were: age, menopause history, BMI, WWI, HbA1c, WC, TC, LDL-C, PTH, N-mid Osteocalcin, diabetic retinopathy and P1NP

Table 7 Weight-adjusted waist index estimated according to gender

Gender	AUC (CI)	*p* values	WWI (sensibility-specificity)
Female (*N* = 161)	0.715 (0.631–0.798)	< 0.001	11.247 cm/√kg (S: 70.3%; E: 71.1%)
Male (*N* = 153)	0.686 (0.529–0.842)	0.011	11.257 cm/√kg (S: 61.1%; E: 80.7%)

Abbreviations: WWI: weight-adjusted waist index; AUC: Area under the curve; CI: confidence interval; S: sensibility; E: specificity

To maintain homeostatic relationships in adult life and aging, bones adapt their mass and shape in response to changes in the load generated by muscle contraction [41]. Muscle contraction contributes to the normal growth and development of bones [42, 43]. Muscle mass loss may lead to osteoporosis [44]. Additionally, muscles are secretory endocrine organs that secrete myokines, such as interleukin 15 and 8, and irisin, which regulate bone mineral content [45–47].

The strength and structural integrity of bones deteriorate with age [48]. Previous research has consistently demonstrated an inverse relationship between age and TBS [49]. Our study corroborates this association, showing that TBS decreases with advancing age in both sexes. Postmenopausal women experience significant hormonal changes, with declining estrogen levels being a major contributor to osteoporosis due to reduced bone protection [50, 51]. Menopause also induces phenotypic changes in bone marrow mesenchymal stem cells, favoring adipogenesis over osteogenesis, thereby promoting an osteoporotic phenotype [52–54]. Consistent with these findings, our research recognized menopause as an independent risk factor for decreased TBS in females with T2D.

Our study identified several factors influencing BMD, particularly within the female cohort. Notably, no significant associations of BMD with any factors, including WWI, were observed in the male group. This suggests that, in adults with T2D, body fat is not significantly related to bone mass. Given that many patients with T2D are overweight, this may indicate that increased body fat does not fully account for impaired bone health and fracture risk through bone mass loss alone. The observed positive correlation between HbA1c and BMD is noteworthy. This contrasts with the findings of previous studies reporting a negative relationship between HbA1c and BMD in postmenopausal women [44, 55]. Conversely, factors such as age, N-mid osteocalcin level, and diabetic retinopathy were negatively associated with BMD in our study. Inverse relationships between age, diabetic retinopathy, and BMD have been extensively documented in previous studies [50, 52, 53, 56–58]. A novel finding of our study is that the N-mid osteocalcin level was negatively correlated with BMD in female patients with T2D. However, the underlying mechanisms remain unclear.

This study has some limitations. First, its cross-sectional design precludes the establishment of causal relationships. Second, the relatively small sample size may not be fully representative of the broader T2D population. Additionally, this study did not include sex hormone indicators that affect bone metabolism. Nonetheless, our study has notable strengths. To the best of our knowledge, it is the first to incorporate WWI as a variable in bone research among patients with T2D, providing a comprehensive analysis of factors affecting both BMD and TBS in this population.

Conclusion

In conclusion, our findings indicate that WWI, a novel and potentially more accurate indicator of body fat levels, is associated with poor bone quality rather than solely low bone mass in Chinese patients with T2D. Thus, it is essential to focus on changes in bone quality, as bone mass alone may not fully capture bone health in patients with T2D with high WWI. In our study, adopting 11.25 cm/√kg as a cut-off threshold demonstrates superior effectiveness in predicting degraded TBS. Additionally, through its simple calculation, WWI provides valuable insights into the interplay between body fat, muscle mass, and bone architecture. Consequently, it could function as a valuable tool for predicting fracture risk within the Chinese population with T2D.

Abbreviations

T2D	Type 2 diabetes
BMD	Bone mineral density
TBS	Trabecular bone score
WWI	Weight-adjusted waist index
DXA	Dual-energy X-ray absorptiometry
WC	Waist circumference
BMI	Body mass index
HbA1c	Hemoglobin A1c
P1NP	Procollagen type I N-terminal propeptide
TG	Triglycerides
TC	Total cholesterol
LDL-C	Low-density lipoprotein cholesterol
Ca	Serum calcium
25-(OH)VitD	25-hydroxyvitamin D
PTH	Parathyroid hormone
β-CTX	c-terminal crosslaps of type 1 collagen

Supplementary Information

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Supplementary Material 1

Supplementary Material 2

Supplementary Material 3

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Author contributions

Dehuai Feng and Ling Chen designed the study. Liming Zhou, Xinlian He, Keli Zhao, Jinyang Wan, Sheng Ouyang, Yiting Zheng, Zhimao Cai, and Shaobin Wang collected the data. Shujuan Chen, Liming Zhou, Xinlian He, Keli Zhao, and Shaobin Wang analyzed the data. Dehuai Feng, Junying Liu, and Ningning Bai drafted the manuscript. Dewen Yan and Ling Chen revised the manuscript. We extend our heartfelt gratitude to the following individuals for their invaluable contributions to this study.

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Data availability

All data generated or analyzed during this study are included in the article.

Declarations

Ethical approval and consent to participate

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