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INTERRELATIONSHIPS BETWEEN SARCOPENIC OBESITY, VITAMIN D STATUS, AND INSULIN RESISTANCE IN BULGARIAN POSTMENOPAUSAL WOMEN WITH TYPE 2 DIABETES MELLITUS

INTER-RELAÇÕES ENTRE A OBESIDADE SARCOPÊNICA, OS NÍVEIS DE VITAMINA D E A RESISTÊNCIA À INSULINA EM MULHERES BÚLGARAS NA PÓS-MENOPAUSA COM DIABETES MELLITUS TIPO 2

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Zlatko Kirovakov*
***Burgas State University "Prof. Asen Zlatarov", Burgas, Bulgaria
Orcid: http://orcid.org/0009-0003-7643-5879
kirovakov@yahoo.com

Nikolay Kostadinov*
***Burgas State University "Prof. Asen Zlatarov", Burgas, Bulgaria
Orcid: http://orcid.org/0009-0001-0702-7949
n.kostadinov_m.d@abv.bg

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Abstract
Background: Sarcopenic obesity is increasingly recognized as a complex metabolic condition characterized by the coexistence of excess adiposity and reduced skeletal muscle mass and function. Postmenopausal women are particularly vulnerable to sarcopenic obesity due to hormonal alterations, chronic low-grade inflammation, vitamin D deficiency, and insulin resistance. However, limited data are available regarding the interrelationships between sarcopenic obesity, vitamin D status, and metabolic dysfunction in Bulgarian postmenopausal women with type 2 diabetes mellitus (T2DM). Aim: The present study aimed to investigate the associations between sarcopenic obesity, serum vitamin D concentrations, and insulin resistance in Bulgarian postmenopausal women with T2DM. Materials and Methods: A cross-sectional observational study was conducted at Medical Center Prime Clinic during the period from January 2024 to December 2025. A total of 240 postmenopausal women aged 50-75 years were enrolled, including 120 women with T2DM and 120 apparently healthy postmenopausal controls. Anthropometric measurements, body composition parameters, handgrip strength, fasting glucose, insulin, glycated hemoglobin (HbA1c), lipid profile, inflammatory biomarkers, and serum 25-hydroxyvitamin D [25(OH)D] concentrations were evaluated. Insulin resistance was assessed using the Homeostatic Model Assessment for Insulin

Resumo
Antecedentes: A obesidade sarcopênica é cada vez mais reconhecida como uma condição metabólica complexa, caracterizada pela coexistência de excesso de adiposidade e redução da massa e da função muscular esquelética. As mulheres na pós-menopausa são particularmente vulneráveis à obesidade sarcopênica devido a alterações hormonais, inflamação crônica de baixo grau, deficiência de vitamina D e resistência à insulina. No entanto, há poucos dados disponíveis sobre as inter-relações entre obesidade sarcopênica, estado da vitamina D e disfunção metabólica em mulheres búlgaras na pós-menopausa com diabetes mellitus tipo 2 (DM2). Objetivo: O presente estudo teve como objetivo investigar as associações entre obesidade sarcopênica, concentrações séricas de vitamina D e resistência à insulina em mulheres búlgaras na pós-menopausa com DM2. Materiais e Métodos: Um estudo observacional transversal foi realizado no Medical Center Prime Clinic durante o período de janeiro de 2024 a dezembro de 2025. Um total de 240 mulheres na pós-menopausa com idades entre 50 e 75 anos foram incluídas, incluindo 120 mulheres com DM2 e 120 controles na pós-menopausa aparentemente saudáveis. Foram avaliadas medidas antropométricas, parâmetros de composição corporal, força de preensão manual, glicemia em jejum, insulina, hemoglobina glicada (HbA1c), perfil lipídico, biomarcadores inflamatórios e concentrações séricas de 25-hidroxivitamina D [25(OH)D]. A

Resistance (HOMA-IR). Results: Women with T2DM demonstrated significantly higher body mass index, waist circumference, fasting glucose, HbA1c, HOMA-IR, and hsCRP levels compared with controls ($p<0.001$). In contrast, serum 25(OH)D concentrations, skeletal muscle mass, and handgrip strength were significantly lower in diabetic women ($p<0.001$). Sarcopenic obesity was identified more frequently in the T2DM group compared with controls (42.5% vs. 16.7%, $p<0.001$). Serum vitamin D concentrations correlated negatively with BMI ($r = -0.41$), waist circumference ($r = -0.45$), HOMA-IR ($r = -0.48$), and hsCRP levels ($r = -0.37$), while positive correlations were observed with skeletal muscle mass ($r = 0.39$) and handgrip strength ($r = 0.43$) (all $p<0.001$). Multiple regression analysis identified sarcopenic obesity, serum vitamin D concentration, waist circumference, and hsCRP as independent predictors of insulin resistance. Conclusion: Bulgarian postmenopausal women with T2DM demonstrated significantly increased prevalence of sarcopenic obesity, lower serum vitamin D levels, and greater insulin resistance compared with healthy controls. Sarcopenic obesity and vitamin D deficiency were independently associated with adverse metabolic and inflammatory profiles. Integrated assessment of body composition, muscle function, inflammatory status, and vitamin D concentrations may improve cardiometabolic risk stratification in postmenopausal women.

Keywords: Sarcopenic Obesity. Vitamin D. Insulin Resistance. Type 2 Diabetes Mellitus. Postmenopausal Women.

resistência à insulina foi avaliada utilizando o Modelo Homeostático de Avaliação da Resistência à Insulina (HOMA-IR). Resultados: As mulheres com DM2 apresentaram índice de massa corporal, circunferência da cintura, glicemia de jejum, HbA1c, HOMA-IR e níveis de hsCRP significativamente mais elevados em comparação com as mulheres do grupo controle ($p < 0,001$). Em contrapartida, as concentrações séricas de 25(OH)D, a massa muscular esquelética e a força de preensão manual foram significativamente mais baixas nas mulheres diabéticas ($p < 0,001$). A obesidade sarcopênica foi identificada com maior frequência no grupo com DM2 em comparação com o grupo controle (42,5% vs. 16,7%, $p < 0,001$). As concentrações séricas de vitamina D apresentaram correlação negativa com o IMC ($r = -0,41$), a circunferência da cintura ($r = -0,45$), HOMA-IR ($r = -0,48$) e níveis de hsCRP ($r = -0,37$), enquanto correlações positivas foram observadas com a massa muscular esquelética ($r = 0,39$) e a força de preensão manual ($r = 0,43$) (todas $p < 0,001$). A análise de regressão múltipla identificou a obesidade sarcopênica, a concentração sérica de vitamina D, a circunferência da cintura e a hsCRP como preditores independentes de resistência à insulina. Conclusão: Mulheres búlgaras na pós-menopausa com DM2 demonstraram prevalência significativamente aumentada de obesidade sarcopênica, níveis séricos mais baixos de vitamina D e maior resistência à insulina em comparação com controles saudáveis. A obesidade sarcopênica e a deficiência de vitamina D foram associadas independentemente a perfis metabólicos e inflamatórios adversos. A avaliação integrada da composição corporal, função muscular, estado inflamatório e concentrações de vitamina D pode melhorar a estratificação do risco cardiometabólico em mulheres na pós-menopausa.

Palavras-chave: *Obesidade Sarcopênica. Vitamina D. Resistência à Insulina. Diabetes Mellitus tipo 2. Mulheres na Pós-Menopausa.*

1 INTRODUCTION

Population aging together with the rapidly increasing prevalence of obesity and type 2 diabetes mellitus (T2DM) has become a major public health concern worldwide. Among aging populations, postmenopausal women represent a particularly high-risk group due to hormonal changes, redistribution of adipose tissue, progressive decline in skeletal muscle mass, and deterioration of metabolic homeostasis. These age-related alterations contribute substantially to insulin resistance, metabolic syndrome, cardiovascular disease, frailty, and impaired quality of life (Cruz-Jentoft *et al*., 2019).

Sarcopenia is currently recognized as a progressive skeletal muscle disorder characterized by reduced muscle mass, decreased muscle strength, and impaired physical performance. According to the revised European Working Group on Sarcopenia in Older People (EWGSOP2) criteria, muscle strength represents the primary diagnostic parameter, while reduced muscle quantity and quality confirm the diagnosis (Cruz-Jentoft *et al*., 2019). In recent years, increasing attention has focused on sarcopenic obesity, a complex clinical condition characterized by the coexistence of excess adiposity and sarcopenia. This phenotype has been associated with unfavorable metabolic outcomes, increased frailty, impaired physical function, cardiovascular complications, and increased mortality compared with obesity or sarcopenia alone (Batsis & Villareal, 2018; Donini *et al*., 2022).

Postmenopausal women appear especially prone to developing sarcopenic obesity because of estrogen deficiency, reduced physical activity, mitochondrial dysfunction, and persistent low-grade inflammation. Menopause is frequently accompanied by visceral fat accumulation and accelerated decline in lean body mass, both of which contribute to worsening insulin resistance and increased cardiometabolic risk (Messier *et al*., 2011). In addition, dysfunctional adipose tissue and skeletal muscle impairment may interact through inflammatory pathways involving tumor necrosis factor-alpha (TNF-α), interleukin-6 (IL-6), and C-reactive protein (CRP), thereby aggravating metabolic disturbances (Kalinkovich & Livshits, 2017).

Another factor increasingly implicated in both metabolic and musculoskeletal disorders among postmenopausal women is vitamin D deficiency. Previous Bulgarian studies have also emphasized the clinical importance of hypovitaminosis D and its

association with adverse health outcomes in vulnerable populations (Borissova *et al*., 2013; Kirovakov & Petkova, 2025). Recent Bulgarian studies have additionally demonstrated associations between obesity and reduced vitamin D concentrations in overweight adults (Nikolova *et al*., 2025). Similarly, Bulgarian studies in postmenopausal women have demonstrated high prevalence of vitamin D insufficiency and disturbances in calcium-phosphorus metabolism associated with adverse musculoskeletal outcomes (Simeonova *et al*., 2020). Beyond its established role in calcium-phosphate homeostasis and bone metabolism, vitamin D exerts multiple pleiotropic effects on skeletal muscle function, immune regulation, adipogenesis, and glucose metabolism. The widespread distribution of vitamin D receptors in pancreatic β-cells, adipocytes, and skeletal muscle tissue further supports its potential role in insulin secretion and insulin sensitivity (Bouillon *et al*., 2019).

Several epidemiological studies have demonstrated that low serum 25-hydroxyvitamin D [25(OH)D] concentrations are associated with increased risk of obesity, metabolic syndrome, insulin resistance, and T2DM (Pittas *et al*., 2019). Vitamin D deficiency may impair insulin signaling pathways, promote chronic inflammation, and exacerbate skeletal muscle dysfunction. Furthermore, obesity itself is strongly associated with lower circulating vitamin D concentrations due to volumetric dilution, sequestration within adipose tissue, reduced bioavailability, decreased outdoor physical activity, and altered metabolic regulation (Wortsman *et al*., 2000; Pereira-Santos *et al*., 2015). Recent experimental and clinical studies additionally indicate that vitamin D deficiency may contribute to the pathogenesis of sarcopenia. Lower vitamin D status has been associated with reduced muscle strength, impaired physical performance, increased risk of falls, and frailty in older adults (Remelli *et al*., 2019). At the same time, insulin resistance may accelerate muscle catabolism and intramuscular fat accumulation, creating a complex bidirectional relationship between metabolic dysfunction and sarcopenic obesity. Despite growing international interest in the relationship between vitamin D and metabolic disorders, data regarding the combined effects of sarcopenic obesity, vitamin D deficiency, and insulin resistance in Eastern European populations remain limited. Bulgaria is characterized by increasing prevalence of obesity and T2DM, particularly among older adults, reflecting broader epidemiological trends observed across Eastern Europe (Tsvetkova & Mihaylova, 2021; International Diabetes Federation [IDF], 2025).

Nevertheless, relatively few studies have specifically explored these interrelated metabolic disturbances in Bulgarian postmenopausal women. A better understanding of the interactions between body composition abnormalities, vitamin D status, and metabolic dysfunction may facilitate earlier identification of high-risk individuals and support development of targeted preventive and therapeutic strategies. Therefore, the present study aimed to investigate the interrelationships between sarcopenic obesity, serum vitamin D concentrations, and insulin resistance in Bulgarian postmenopausal women with T2DM.

2 MATERIALS AND METHODS

2.1 Study design and participants

A cross-sectional observational study was conducted at Medical Center Prime Clinic during the period from January 2024 to December 2025. The study included a total of 240 postmenopausal women aged between 50 and 75 years.

Participants were divided into two groups:

Clinical group: postmenopausal women diagnosed with type 2 diabetes mellitus (T2DM);

Control group: apparently healthy postmenopausal women without diabetes mellitus.

All participants underwent detailed clinical, anthropometric, and laboratory evaluation. The study protocol was approved by the local Ethics Committee of Medical Center Prime Clinic, and all participants provided written informed consent prior to enrollment.

2.2 Inclusion criteria

2.2.1 Clinical group

Participants were eligible for inclusion in the clinical group if they fulfilled the following criteria:

- Female sex;
- Age between 50 and 75 years;
- Natural menopause defined as absence of menstruation for at least 12 consecutive months; Established diagnosis of T2DM according to the American Diabetes Association criteria; and
- Ability and willingness to provide written informed consent.

2.2.2 Control group

Participants were included in the control group if they met the following criteria:

- Female sex;
- Age between 50 and 75 years;
- Natural menopause for at least 12 months;
- Absence of previously diagnosed diabetes mellitus;
- Normal fasting plasma glucose and glycated hemoglobin values;
- Absence of acute or chronic inflammatory disease;
- Written informed consent.

2.3 Exclusion criteria

Participants from both groups were excluded in the presence of any of the following conditions:

- Type 1 diabetes mellitus;
- Active malignant disease;
- Severe hepatic or renal impairment;
- Autoimmune or systemic inflammatory disorders;
- Chronic corticosteroid therapy;
- Current treatment with anti-obesity medications;
- Hormone replacement therapy during the previous 6 months;
- Acute infection during the previous 4 weeks;
- Severe cardiovascular events during the previous 6 months;
- Chronic neuromuscular disorders affecting muscle function;

- Current vitamin D supplementation exceeding standard prophylactic doses;
- Alcohol abuse or severe psychiatric disorders.
- Clinical and Anthropometric Assessment

Demographic and clinical data were obtained through structured interviews and medical documentation review. Anthropometric measurements included body weight, height, body mass index (BMI), waist circumference, hip circumference, and waist-to-hip ratio (WHR). Body composition parameters were evaluated using bioelectrical impedance analysis (BIA), including: total body fat percentage; skeletal muscle mass; visceral fat level; and appendicular skeletal muscle mass. Muscle strength was assessed using handgrip dynamometry. Sarcopenia was defined according to the revised European Working Group on Sarcopenia in Older People (EWGSOP2) criteria.

2.4 Laboratory analyses

Venous blood samples were collected in the morning after overnight fasting of at least 8-12 hours. The following laboratory parameters were assessed:

- Glycemic Parameters
- fasting plasma glucose;
- fasting insulin;
- glycated hemoglobin (HbA1c);
- Homeostatic Model Assessment for Insulin Resistance (HOMA-IR).

Insulin resistance was calculated using the formula: HOMA-IR was calculated using the following formula**: HOMA-IR** = [Fasting insulin (μU/mL) × Fasting glucose (mmol/L)] / 22.5, according to the method described by Matthews *et al*. (1985).

3 RESULTS

3.1 Characteristics of the study population

A total of 240 postmenopausal women were included in the present study. The clinical group consisted of 120 women diagnosed with type 2 diabetes mellitus (T2DM), while the control group included 120 apparently healthy postmenopausal women without

diabetes mellitus. Women with T2DM demonstrated significantly higher anthropometric indices associated with obesity and metabolic dysfunction. In particular, body mass index (BMI), waist circumference, and body fat percentage were significantly elevated in the diabetic group compared with controls. In addition, diabetic women exhibited significantly reduced skeletal muscle mass and lower handgrip strength values. Metabolic parameters including fasting glucose, glycated hemoglobin (HbA1c), fasting insulin, and HOMA-IR were significantly higher among women with T2DM. Serum 25-hydroxyvitamin D [25(OH)D] concentrations were significantly lower in diabetic participants, while inflammatory activity assessed by hsCRP was markedly increased. The demographic, anthropometric, and biochemical characteristics of the study population are presented in Table 1.

Table 1

Demographic, Anthropometric, and Metabolic Characteristics of the Study Population

Parameter	T2DM Group (n = 120)	Control Group (n = 120)	p-value
Age (years)	63.4 ± 6.8	61.9 ± 5.9	0.087
BMI (kg/m²)	32.1 ± 5.3	27.4 ± 4.2	<0.001
Waist circumference (cm)	101.6 ± 11.4	88.7 ± 9.8	<0.001
Body fat (%)	41.8 ± 6.2	35.9 ± 5.7	<0.001
Skeletal muscle mass (kg)	21.4 ± 3.1	24.2 ± 3.4	<0.001
Handgrip strength (kg)	18.2 ± 4.3	24.8 ± 5.1	<0.001
Fasting glucose (mmol/L)	8.7 ± 2.1	5.1 ± 0.6	<0.001
HbA1c (%)	7.8 ± 1.2	5.4 ± 0.4	<0.001
HOMA-IR	4.9 ± 1.8	2.1 ± 0.9	<0.001
25(OH)D (ng/mL)	18.6 ± 7.2	28.9 ± 8.1	<0.001
hsCRP (mg/L)	5.8 ± 2.6	2.4 ± 1.1	<0.001

The prevalence of sarcopenic obesity was significantly higher among women with T2DM compared with healthy controls. Overall, sarcopenic obesity was identified in 42.5% of diabetic women and in 16.7% of control participants ($p<0.001$). Women with sarcopenic obesity demonstrated substantially lower serum vitamin D levels, reduced muscle strength, and significantly higher insulin resistance indices compared with women without sarcopenic obesity. Moreover, inflammatory biomarkers were significantly elevated in this subgroup. Comparative analyses between women with and without sarcopenic obesity are summarized in Table 2.

Table 2

Comparison Between Women With and Without Sarcopenic Obesity

Parameter	Sarcopenic Obesity (n = 71)	Non-Sarcopenic Obesity (n = 169)	p-value
BMI (kg/m²)	33.8 ± 5.9	28.1 ± 4.8	<0.001
Handgrip strength (kg)	16.4 ± 3.7	24.9 ± 4.9	<0.001
Skeletal muscle mass (kg)	19.7 ± 2.8	24.6 ± 3.5	<0.001
HOMA-IR	5.6 ± 2.0	2.8 ± 1.3	<0.001
25(OH)D (ng/mL)	16.1 ± 6.3	26.8 ± 7.9	<0.001
hsCRP (mg/L)	6.3 ± 2.8	3.1 ± 1.5	<0.001

Correlation analyses were subsequently performed to evaluate the relationships between serum vitamin D concentrations and markers of adiposity, muscle function, insulin resistance, and inflammation. Serum 25(OH)D levels demonstrated significant negative correlations with BMI, waist circumference, HbA1c, HOMA-IR, and hsCRP concentrations. Conversely, positive associations were identified between vitamin D concentrations and both skeletal muscle mass and handgrip strength. These findings suggest that lower vitamin D status may contribute to worsening metabolic dysfunction and impaired musculoskeletal health in postmenopausal women. The correlations between serum vitamin D levels and clinical parameters are presented in Table 3.

Table 3

Correlation Between Serum 25(OH)D and Clinical Parameters

Variable	Correlation coefficient (r)	p-value
BMI	−0.41	<0.001
Waist circumference	−0.45	<0.001
HOMA-IR	−0.48	<0.001
HbA1c	−0.35	<0.001
hsCRP	−0.37	<0.001
Handgrip strength	0.43	<0.001
Skeletal muscle mass	0.39	<0.001

To further investigate determinants of insulin resistance, multivariate linear regression analysis was performed using HOMA-IR as the dependent variable. The analysis identified sarcopenic obesity, serum 25(OH)D concentration, waist

circumference, and hsCRP as independent predictors of insulin resistance after adjustment for potential confounding factors. Among all variables included in the model, sarcopenic obesity demonstrated the strongest positive association with HOMA-IR, whereas serum vitamin D concentrations showed an independent inverse association. The results of the regression analysis are shown in Table 4.

Table 4

Independent Predictors of HOMA-IR in Multiple Regression Analysis

Variable	β-coefficient	Standard Error	p-value
Sarcopenic obesity	0.39	0.07	<0.001
25(OH)D	−0.31	0.05	<0.001
Waist circumference	0.28	0.06	0.002
hsCRP	0.24	0.04	0.006

Collectively, the present findings indicate that sarcopenic obesity and vitamin D deficiency are closely associated with insulin resistance and chronic low-grade inflammation in Bulgarian postmenopausal women with T2DM. The combined evaluation of body composition, muscle function, and vitamin D status may therefore provide clinically useful information for metabolic risk stratification in this vulnerable population.

4 DISCUSSION

The present study explored the complex associations between sarcopenic obesity, vitamin D status, and insulin resistance in Bulgarian postmenopausal women with type 2 diabetes mellitus (T2DM). Our findings demonstrated that women with T2DM exhibited significantly greater adiposity, reduced skeletal muscle mass and muscle strength, higher inflammatory activity, and lower serum 25-hydroxyvitamin D [25(OH)D] concentrations compared with healthy postmenopausal controls. In addition, sarcopenic obesity emerged as a strong independent predictor of insulin resistance in this population. These observations further support the growing evidence that sarcopenic obesity represents a metabolically unfavorable phenotype associated with increased cardiometabolic risk and functional impairment (Donini *et al*., 2022; Kalinkovich & Livshits, 2017).

The mechanisms underlying these associations are likely multifactorial. Hormonal alterations occurring after menopause, particularly estrogen deficiency, are known to promote visceral adiposity, chronic low-grade inflammation, and progressive decline in skeletal muscle mass. Together, these changes may substantially worsen insulin sensitivity and metabolic homeostasis (Messier *et al*., 2011). In parallel, reduced physical activity and age-related anabolic resistance may further contribute to the development of sarcopenic obesity in postmenopausal women (Cruz-Jentoft *et al*., 2019). One of the most notable findings of the present study was the significantly lower serum vitamin D concentrations observed among women with T2DM and sarcopenic obesity. We identified significant inverse correlations between serum 25(OH)D levels and BMI, waist circumference, HbA1c, HOMA-IR, and hsCRP concentrations.

These findings are consistent with previous reports demonstrating reduced vitamin D bioavailability in obese individuals and an association between hypovitaminosis D and metabolic dysfunction (Pereira-Santos *et al*., 2015; Pittas *et al*., 2019). Recent Bulgarian data have similarly demonstrated significant associations between obesity and reduced serum vitamin D concentrations among overweight adults (Nikolova *et al*., 2025). The widespread expression of vitamin D receptors in pancreatic β-cells, adipose tissue, and skeletal muscle suggests that vitamin D may play an important role in glucose metabolism and insulin signaling (Bouillon *et al*., 2019). Several experimental studies have proposed that vitamin D deficiency may contribute to insulin resistance through impaired insulin receptor activity, altered intracellular calcium regulation, oxidative stress, and activation of pro-inflammatory pathways.

The complex interactions observed in the present study suggest that sarcopenic obesity, vitamin D deficiency, chronic low-grade inflammation, and insulin resistance may represent interconnected pathophysiological processes in postmenopausal women. Estrogen deficiency, visceral adiposity, skeletal muscle dysfunction, and inflammatory activation appear to contribute synergistically to metabolic deterioration and increased cardiometabolic risk. The proposed mechanisms underlying these relationships are summarized in Figure 1.

Figure 1

Proposed pathophysiological interactions between sarcopenic obesity, vitamin D deficiency, inflammation, and insulin resistance in postmenopausal women.

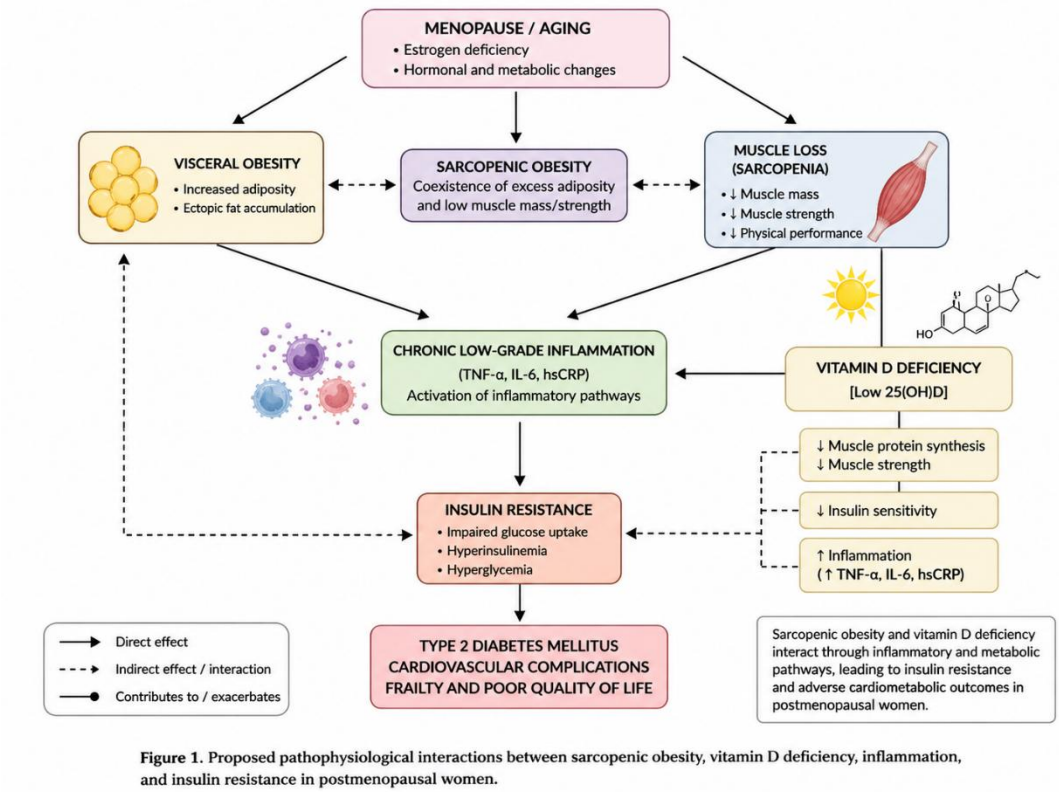

Figure 1. Proposed pathophysiological interactions between sarcopenic obesity, vitamin D deficiency, inflammation, and insulin resistance in postmenopausal women.

As illustrated in Figure 1, menopause-related hormonal alterations may promote visceral adiposity and progressive skeletal muscle loss, thereby contributing to chronic low-grade inflammation and insulin resistance. Concurrent vitamin D deficiency may further aggravate metabolic dysfunction through impaired insulin signaling, reduced muscle protein synthesis, and activation of pro-inflammatory pathways. These interconnected mechanisms may collectively accelerate development of sarcopenic obesity and adverse cardiometabolic outcomes in postmenopausal women.

Another clinically relevant observation was the positive relationship between vitamin D status and muscle strength. Women with lower serum 25(OH)D concentrations demonstrated significantly reduced handgrip strength and lower skeletal muscle mass. Similar findings have been reported in previous studies linking vitamin D deficiency to impaired muscle protein synthesis, mitochondrial dysfunction, sarcopenia, and frailty in older adults (Remelli *et al.*, 2019).

Furthermore, recent meta-analyses of randomized controlled trials have demonstrated that vitamin D supplementation may improve handgrip strength and muscle performance in postmenopausal women (Zhang *et al*., 2022).

5 CONCLUSION

In conclusion, Bulgarian postmenopausal women with T2DM demonstrated significantly increased prevalence of sarcopenic obesity, lower serum vitamin D concentrations, and greater insulin resistance compared with healthy controls. Sarcopenic obesity and vitamin D deficiency were independently associated with adverse metabolic and inflammatory profiles. These findings suggest that integrated evaluation of body composition, muscle function, and vitamin D status may represent a valuable approach for identification of postmenopausal women at increased cardiometabolic risk.

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