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From muscle quality to metabolic health: investigating the association between muscle quality index and metabolic syndrome in adults

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Abstract

Objective Metabolic syndrome (MetS) has a high prevalence in the United States (US); however, limited research comprehensively evaluates the relationship between muscle quality index (MQI) and MetS. This study aims to investigate the association between MQI and MetS.

Methods Adults aged 20–60 years from the 2011–2014 National Health and Nutrition Examination Survey were included. Handgrip strength (HGS) was measured using a dynamometer, and appendicular skeletal muscle mass (ASM) was assessed via dual-energy X-ray absorptiometry. MQI_total was calculated as the sum of HGS from both hands divided by ASM. Weighted multivariable logistic regression models and restricted cubic splines (RCS) were used to explore the association between MQI_total and MetS, and subgroup, interaction, and sensitivity analyses were conducted.

Results A total of 4,503 US residents were included in the study, with 1,165 diagnosed with MetS, yielding a prevalence of 25.9% (1,165/4,503). The weighted multivariable logistic regression model indicated that after adjusting for multiple covariates, MQI was negatively associated with the risk of MetS (odds ratio [OR] = 0.49, 95%CI: 0.32–0.73). Among the different components of MetS, MQI was negatively associated with elevated waist circumference (OR = 0.19, 95%CI: 0.12–0.28), elevated high-density lipoprotein cholesterol (OR = 0.66, 95%CI: 0.51–0.85), and elevated serum triglycerides (OR = 0.66, 95%CI: 0.51–0.85). RCS revealed a negative linear relationship between MQI and MetS ($P < 0.001$, $P_{non-linear} = 0.98$).

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Conclusion Low MQI is associated with an increased risk of MetS, exhibiting a linear relationship. These findings suggest that improving muscle quality may be an effective strategy for the prevention of MetS.

Keywords Muscle quality index, Metabolic syndrome, Prevalence, Odds ratio

Introduction

Metabolic syndrome (MetS) is a cluster of metabolic disorders characterized by insulin resistance, obesity, hyperglycemia, hypertension, and dyslipidemia [1]. The prevalence of MetS is increasing globally. In the United States (U.S.), the prevalence of MetS among adults is high, having increased from 32.9% in 2003 to 34.7% in 2011 [2]. Recent population studies indicated that the prevalence of MetS among U.S. adults had reached to 41.8% in 2018 [3, 4]. According to the Global Burden of Disease Study (GBD) 2021, among the 25 level-3 risk factors contributing to global disease burden, MetS and its components have shown a gradual increase in their share of total disability-adjusted life years (DALYs) [5]. Numerous studies have found that it increases the risk of cardiovascular disease (CVD), diabetes, and stroke, leading to adverse chronic disease outcomes [6, 7]. For instance, a meta-analysis that included 13 cohort studies found that components of metabolic syndrome including low high-density lipoprotein (HDL)-C significantly increased the risk of stroke by 46% [8]. A meta-analysis showed that metabolic syndrome could also increase the risk of cancer in the population, and presented population differences such as gender and age [9]. At the same time, a large cohort study found that the components of MetS were associated with an increased risk of all-cause mortality [10]. Metabolic syndrome and its components have become the top ten risk factors affecting the global burden of disease. Mets has become an urgent global health problem.

European Working Group on Sarcopenia in Older People (EWGSOP) emphasizes that skeletal muscle metabolism and muscle mass decline with age [11]. A 4-year follow-up study conducted in Japan, which enrolled 1,099 subjects aged ≥ 60 years, showed that after the age of 50, lower limb muscle strength decreases by 1.5–5.0% per year, and appendicular skeletal muscle mass (ASM) declines by 1–2% per year [12]. The decline in muscle mass and strength increases the risk of chronic diseases such as CVD, abnormal glucose metabolism, chronic obstructive pulmonary disease, and cancer [13]. Compared to muscle strength and muscle mass, the MQI integrates both handgrip strength (dominant and non-dominant) and ASM, reflecting both the quality and quantity of muscle, making it a more comprehensive indicator that is widely used [14, 15]. Previous research has found that low MQI was associated with the risk of periodontitis [16]CVD [17]and sleep problems [18]. Previous studies have reported a negative association between muscle strength and MetS in men [19]. Evidence also suggests that the decline in skeletal muscle mass may promote insulin resistance and hyperglycemia, thereby accelerating the progression of MetS [20, 21]. However, research on the association between comprehensive muscle mass indicators and MetS remains limited.

Herein, we aim to investigate the association between MQI, a composite measure of muscle strength and mass, and MetS in U.S. adults aged 20 to 60 years, thereby supplementing the limited research on integrated muscle health indicators and their metabolic health implications.

Materials and methods

This cross-sectional study utilized data from the 2011–2014 National Health and Nutrition Examination Survey (NHANES) cycles. NHANES is a nationally representative survey that collects information on health, nutrition, and lifestyle behaviors across various demographic groups in the U.S. The NHANES was approved by the Research Ethics Review Board of the National Center for Health Statistics. Data used in this study were obtained from the following website: (https://wwwn.cdc.gov/nchs/nhanes/Default.aspx). The study included individuals who met the following criteria: (1) age: 20–60 years; (2) complete handgrip strength (HGS) data; (3) complete data on MetS diagnostic criteria (including National Cholesterol Education Program Adult Treatment Panel III (NCEPA ATP III) and International Diabetes Federal-2009(IDF-2009); (4) complete data on other covariates. A total of 4,503 participants were included in the final analysis. See Fig. 1 for further details.

Exposure measurement

MQI is a composite index that combines HGS and appendicular skeletal muscle mass (ASM) to assess muscle quality [14]. HGS was measured using a Takei dynamometer (TKK5401; HGS was measured using a Takei dynamometer (TKK5401; Takei Scientific Instruments, Tokyo, Japan), and ASM was assessed using dual-energy X-ray absorptiometry (DXA), calibrated daily [22]. MQI consists of three components: MQI_arm, defined as the ratio of dominant HGS to the dominant arm's ASM ($HGS_{dominant}/ASM_{dominant-arm}$); MQI_app, defined as the ratio of dominant HGS to total ASM ($HGS_{dominant}/ASM_{total}$); and MQI_total, defined as the sum of handgrip strength from both the dominant and non-dominant hands divided by total ASM (HGS_{total}/ASM_{total}) [14]. Considering the differences in body composition among different racial and gender groups [23]cut-off values were

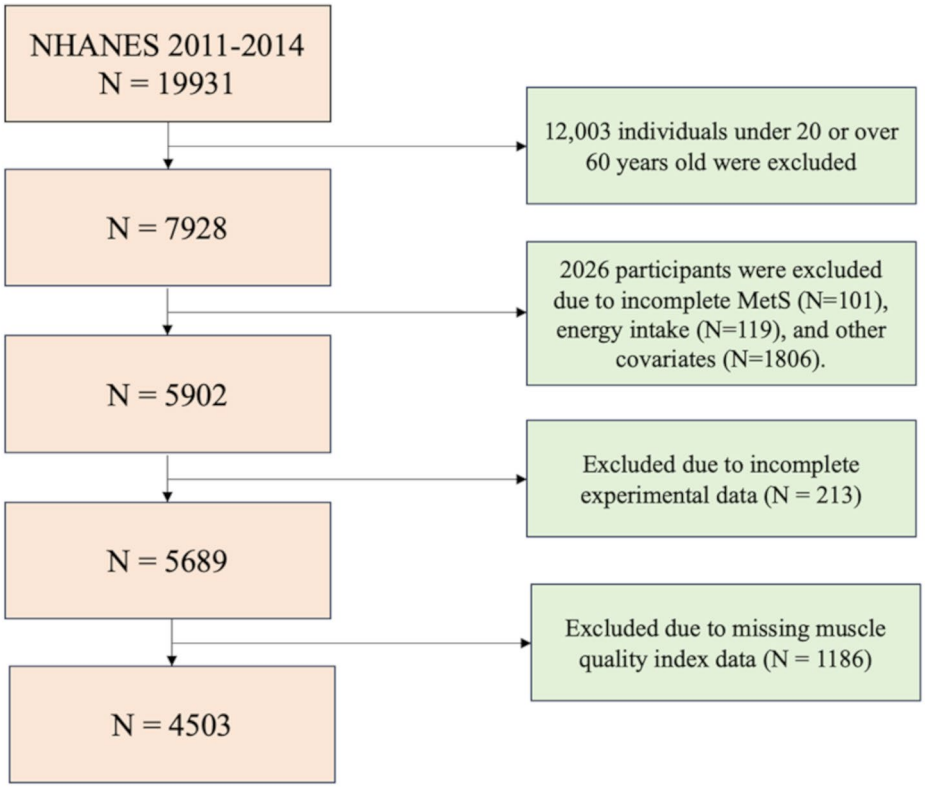

Fig. 1 The flowchart of this study. Abbreviations: NHANES, National Health and Nutrition Examination Survey; MetS, Metabolic Syndrome

set for MQI_total. Low MQI_total was defined as being below 1 standard deviation (SD) of the reference mean for young adults, and very low MQI_total was defined as being below 2 SDs of the reference mean for young adults. The young adult group included both males and females aged 20–39 years with a normal body mass index (BMI) range.

Definition of outcomes

The diagnosis of MetS was based on the criteria established by National Cholesterol Education Program Adult Treatment Panel III (NCEP ATP III) [24]. MetS was diagnosed when three or more of the following five conditions were present: (1) Central obesity: waist circumference ≥ 102 cm for men, ≥ 88 cm for women; (2) Hypertriglyceridemia: serum triglycerides ≥ 150 mg/dL; (3) Low HDL cholesterol: serum HDL cholesterol < 40 mg/dL for men, < 50 mg/dL for women; (4) Hypertension: systolic blood pressure (SBP) ≥ 130 mmHg, diastolic blood pressure (DBP) ≥ 85 mmHg, or current antihypertensive treatment; (5) High fasting glucose: fasting glucose ≥ 100 mg/dL, or current antidiabetic treatment. All data were collected using standardized methods. Another diagnosis of MetS was based on the criteria established by the International Diabetes Federation 2009 (IDF-2009). The detailed IDF-2009 criteria are described in the Supplementary Method. MetS diagnosed according to the IDF-2009 criteria was used only for sensitivity analysis.

Definition of covariates

The study included the following characteristics: age (years), sex (male or female), marital status (unmarried, divorced/separated/widowed, married/cohabitating), education level (less than high school, high school, college or above), race/ethnicity (non-Hispanic White, Mexican American, non-Hispanic Black, other races), and poverty income ratio (PIR) categorized into three levels: low income (< 1.3), middle income (1.3–3.5), and high income (> 3.5). BMI was categorized into three groups: underweight (< 18.5), normal weight (18.5–24.9), and overweight/obese (≥ 25.0) [25]. Smoking status was classified into three categories: never smokers (less than 100 cigarettes in lifetime), former smokers (more than 100 cigarettes in lifetime but not currently smoking), and current smokers (more than 100 cigarettes in lifetime and currently smoking daily) [26]. Alcohol consumption was classified as: never drinkers (fewer than 12 drinks in a lifetime), former drinkers (12 or more drinks in the past year but not in the last year, or 12 or more drinks in a lifetime but not in the last year), light drinkers (≤ 1 drink per day for women, ≤ 2 drinks per day for men), moderate

drinkers (≥ 2 drinks per day for women, ≥ 3 drinks per day for men, or binge drinking 2–5 times per month), and heavy drinkers (≥ 3 drinks per day for women, ≥ 4 drinks per day for men, or binge drinking > 5 times per month) [27]. Physical activity status was calculated according to weekly metabolic equivalent of task (MET) minutes (MET-minutes/week), which included the sum of the following three aspects: work-related physical activity (vigorous work days × vigorous work minutes × 8, moderate work days × moderate work minutes × 4), recreational activities (vigorous recreational activity days × vigorous recreational activity minutes × 8, moderate recreational activity days × moderate recreational activity minutes × 4), and walking or bicycling (walking or bicycling frequency × walking or bicycling duration × 4). The sum of these three components was classified into three levels: low (< 360 min/week), moderate (360–3600 min/week), and high (> 3600 min/week) [28]. The study also considered the history of hypertension (systolic blood pressure[SBP] ≥ 140 mmHg and/or diastolic blood pressure[DBP] ≥ 90 mmHg, use of antihypertensive medication, or a diagnosis of hypertension by a physician or healthcare professional), history of hyperlipidemia (defined by any of the following: triglycerides ≥ 150 mg/dL, total cholesterol [TC] ≥ 200 mg/dL, low-density lipoprotein cholesterol[LDL-C] ≥ 130 mg/dL, or high-density lipoprotein cholesterol[HDL-C] ≤ 40 mg/dL for men and ≤ 50 mg/dL for women), and history of diabetes (defined by any of the following: diagnosis of diabetes by a physician or healthcare professional, use of antidiabetic medication or insulin, random blood glucose ≥ 11.1 mmol/L, glycated hemoglobin (HbA1c level) ≥ 6.5%, fasting glucose ≥ 7.0 mmol/L, or 2-hour oral glucose tolerance test (OGTT) blood glucose level ≥ 11.1 mmol/L). Additionally, energy intake (kcal/day), as well as blood biochemical markers such as [HbA1c, %], alanine aminotransferase [ALT, U/L], aspartate aminotransferase [AST, U/L)], serum creatinine (μmol/L), serum uric acid (μmol/L), and total cholesterol (mmol/L), were included.

Statistical analysis

Statistical analyses were conducted using R version 4.3.1. Due to NHANES' multi-stage sampling design, we applied weighted calculations in accordance with NHANES guidelines. Data from the 2011–2012 and 2013–2014 survey cycles were used, with the sample weight calculated as (1/2) × WTMEC2YR 11–12 + (1/2) × WTMEC2YR 13–14, where WTMEC2YR 11–12 and WTMEC2YR 13–14 represent the weight coefficients for each cycle. Continuous variables are presented as mean ± SD, while categorical variables are shown as percentages (%). To examine the association between MQI and MetS, weighted binary logistic regression was used, with three models developed sequentially: (1) Model 1: Unadjusted; (2) Model 2: Adjusted for gender, age, education level, race, and PIR; (3) Model 3: Further adjusted for smoking status, alcohol consumption, METs, serum ALT, AST, uric acid, total cholesterol, creatinine, energy intake.

To assess the robustness of the results, three sensitivity analyses were performed. First, subgroup analyses and interaction tests were conducted based on covariates such as age group, gender, and race/ethnicity. Second, associations between MQI and the components of MetS—elevated waist circumference, hypertension, reduced HDL-C, elevated triglycerides, and elevated fasting glucose—were analyzed. Third, restricted cubic spline regression was applied to explore the relationship between MQI and MetS. Lastly, to account for variations in MetS diagnostic criteria, IDF-2009 criteria were used. All statistical tests were two-sided, with a significance level of $P < 0.05$.

Results

After preliminary data processing, a total of 4,503 participants were included in this study. The basic characteristics of the study population were shown in Table 1. Among the 4,503 participants, 1,165 were diagnosed with MetS, resulting in a prevalence of 25.87% (1,165/4,503). The average age of MetS patients was 44.26 ± 0.44 years, while the average age of non-MetS participants was 37.49 ± 0.44 years. Compared to individuals without MetS, those with MetS were generally older, had lower education levels, and exhibited lower levels of physical activity. In terms of laboratory markers, MetS patients were more likely to have elevated HbA1c, ALT, AST, and total cholesterol levels. Regarding MQI, the proportion of participants with normal MQI (including MQI_total, MQI_arm, and MQI_app) was lower in the MetS group compared to the non-MetS group, indicating overall lower muscle quality in MetS patients. The association between age and MQI was presented in Supplementary Table S1, and the variance inflation factors for all covariates were provided in Supplementary Table S2.

Table 2 presented the association between MQI_total and the risk of MetS as well as its components. Weighted logistic regression analysis showed a negative association between MQI_total and the odds ratio of MetS across all models (Model 1: OR = 0.34, 95% CI: 0.29–0.39, $P < 0.0001$; Model 2: OR = 0.33, 95% CI: 0.28–0.39, $P < 0.0001$; Model 3: OR = 0.49, 95% CI: 0.32–0.73, $P = 0.02$). Among the components of MetS, after adjusting for relevant covariates, MQI_total was negatively associated with elevated waist circumference (Model 3: OR = 0.19, 95% CI: 0.12–0.28, $P = 0.003$), and negatively associated with hypertension (Model 3: OR = 0.82, 95% CI: 0.61–1.09, $P = 0.11$), elevated fasting glucose (Model 3: OR = 0.84, 95% CI: 0.62–1.14, $P = 0.17$), reduced serum

Table 1 The characteristics of the study population

Variables	Overall	Non-MetS	MetS	*P* value
		N = 3338	*N* = 1165	
Age (years)	39.21 ± 0.42	37.49 ± 0.44	44.26 ± 0.44	< 0.001
Gender, %				0.88
Male	2177(52.16)	1565(52.32)	612(51.96)	
Female	2326(47.84)	1773(47.68)	553(48.04)	
Race, %				0.01
Non-Hispanic White	1876(65.85)	1359(65.26)	517(67.57)	
Mexican American	553(9.36)	370(8.82)	183(10.97)	
Non-Hispanic Black	946(10.62)	715(10.77)	231(10.17)	
Others	1128(14.17)	894(15.15)	234(11.28)	
Educational levels, %				< 0.001
Above high school	2825(66.46)	2184(69.02)	641(58.98)	
High school	955(20.89)	661(19.00)	294(26.42)	
Below high school	723(12.65)	493(11.98)	230(14.60)	
Marital status, %				< 0.001
Never married	1266(25.46)	1083(29.37)	183(14.02)	
Divorced/Seperated/Widowed	634(13.29)	410(11.81)	224(17.66)	
Married/Living with partner	2603(61.25)	1845(58.82)	758(68.32)	
PIR, %				0.09
Q1 (< 1.29)	1504(23.93)	1075(23.38)	429(25.53)	
Q2 (1.29–3.48)	1498(33.44)	1095(32.70)	403(35.63)	
Q3 (> 3.48)	1501(42.63)	1168(43.92)	333(38.84)	
BMI, %				< 0.001
Q1 (< 25.0)	1454(31.25)	1393(40.21)	61(5.03)	
Q2 (25.0–30.0)	1423(33.65)	1140(37.13)	283(23.45)	
Q3 (> 30.0)	1626(35.10)	805(22.66)	821(71.52)	
Smoking status, %				< 0.001
Never	2680(58.27)	2056(60.53)	624(51.64)	
Former	763(19.18)	536(17.92)	227(22.88)	
Now	1060(22.55)	746(21.55)	314(25.48)	
Drinking status, %				< 0.001
Former	483(10.00)	289(8.00)	194(15.91)	
Never	544(9.21)	386(8.92)	158(10.05)	
Mild	1453(33.32)	1109(33.78)	344(31.97)	
Moderate	841(20.11)	653(20.98)	188(17.55)	
Heavy	1182(27.36)	901(28.32)	281(24.52)	
METs, minute/week				0.02
Q1 (< 360)	1522(32.23)	1082(31.04)	440(35.74)	
Q2 (360–3600)	1491(34.01)	1088(33.77)	403(34.70)	
Q3 (> 3600)	1490(33.76)	1168(35.19)	322(29.56)	
Hypertension				< 0.001
No	3245(72.75)	2718(82.47)	527(44.29)	
Yes	1258(27.25)	620(17.53)	638(55.71)	
Hyperlipidemia				< 0.001
No	1663(35.79)	1597(46.17)	66(5.37)	
Yes	2840(64.21)	1741(53.83)	1099(94.63)	
Diabetes				< 0.001
No	4039(91.60)	3237(97.70)	802(73.76)	
Yes	464(8.40)	101(2.30)	363(26.24)	
Energy intake, kcal/day	2302.59 ± 18.90	2297.79 ± 19.54	2316.64 ± 51.74	0.74
HbA1c, %	5.50 ± 0.02	5.31 ± 0.01	6.04 ± 0.05	< 0.001
ALT, U/L	26.52 ± 0.36	24.56 ± 0.38	32.28 ± 0.81	< 0.001
AST, U/L	25.72 ± 0.32	24.94 ± 0.26	27.98 ± 0.89	0.001

Table 1 (continued)

Variables	Overall	Non-MetS	MetS	*P* value
		N = 3338	*N* = 1165	
Creatinine, μmol/L	76.87 ± 0.47	76.92 ± 0.53	76.73 ± 0.66	0.80
Uric acid, μmol/L	318.64 ± 1.86	309.58 ± 2.05	345.16 ± 2.85	< 0.001
Total cholesterol, mmol/L	4.97 ± 0.02	4.89 ± 0.03	5.22 ± 0.04	< 0.001
MQI_total				< 0.001
Extremely low	1067(25.82)	609(20.45)	458(41.57)	
Low	903(18.48)	620(17.77)	283(20.57)	
Normal	2533(55.69)	2109(61.79)	424(37.86)	
MQI_.arm				< 0.001
Extremely low	646(16.74)	308(11.43)	338(32.28)	
Low	922(20.61)	598(19.05)	324(25.21)	
Normal	2935(62.65)	2432(69.52)	503(42.51)	
MQI_.app				< 0.001
Extremely low	659(17.08)	342(12.54)	317(30.38)	
Low	980(22.01)	633(19.93)	347(28.11)	
Normal	2864(60.91)	2363(67.53)	501(41.51)	

MQI_arm: Ratio of dominant HGS to the dominant arm's ASM

MQI_app: Ratio of dominant HGS to total ASM

MQI_total: Sum of HGS of both hands divided by total ASM

Abbreviations: MetS, metabolic syndrome; PIR, poverty income ratio; BMI, body mass index; METs, metabolic equivalent of tasks; HbA1c, glycated hemoglobin ALT, alanine aminotransferase; AST, aspartate aminotransferase; HGS, handgrip strength; ASM, appendicular skeletal muscle

Table 2 Associations between the muscle quality index and metabolic syndrome, along with its components

MetS and its components	OR (95% CI)	*P* value
MetS[a] (1165/4503)		
Model 1	0.34 (0.29, 0.39)	< 0.001
Model 2	0.33 (0.28, 0.39)	< 0.001
Model 3	0.49 (0.32, 0.73)	0.02
Elevated waist circumference (2250/4503)		
Model 1	0.17 (0.14, 0.19)	< 0.001
Model 2	0.16 (0.13, 0.19)	< 0.001
Model 3	0.19 (0.12, 0.28)	0.003
Hypertension (1258/4503)		
Model 1	0.54 (0.47, 0.63)	< 0.001
Model 2	0.61 (0.52, 0.71)	< 0.001
Model 3	0.82 (0.61, 1.09)	0.11
Elevated fasting glucose (933/4503)		
Model 1	0.56 (0.46, 0.67)	< 0.001
Model 2	0.54 (0.44, 0.67)	< 0.001
Model 3	0.84 (0.62, 1.14)	0.17
Reduced high-density lipoprotein cholesterol (1412/4503)		
Model 1	0.53 (0.46, 0.61)	< 0.001
Model 2	0.52 (0.45, 0.60)	< 0.001
Model 3	0.66 (0.51, 0.85)	0.01
Elevated total triglycerides (1549/4503)		
Model 1	0.73 (0.62, 0.85)	< 0.001
Model 2	0.64 (0.55, 0.75)	< 0.001
Model 3	0.77 (0.59, 0.97)	0.03

Model 1: Unadjusted for any covariates; Model 2: Adjusted for age, gender, educational level, ethnicity, PIR, and marital status, building on Model 1; Model 3: Further adjusted for alcohol consumption, smoking status, METs, ALT, AST, uric acid, HbA1c, total cholesterol, energy intake (kcal/day), and serum creatinine

[a] Criteria for MetS are based on the NCEP-ATP III guidelines

Abbreviations: MetS, metabolic syndrome. OR, odd ratios. CI: confidence interval. PIR, poverty income ratio. MET, metabolic equivalent of task. ALT, alanine aminotransferase. AST, aspartate aminotransferase. HbA1c, glycated hemoglobin. NCEP-ATP III, National Cholesterol Education Program Adult Treatment Panel III

HDL cholesterol (Model 3: OR = 0.66, 95% CI: 0.51–0.85, $P = 0.01$), and elevated serum triglycerides (Model 3: OR = 0.77, 95% CI: 0.59–0.97, $P = 0.03$).

The dose-response relationship between MQI_total and MetS indicated that an increase in MQI was associated with a reduced risk of developing MetS. However, the nonlinearity test showed a *P*-value greater than 0.05, suggesting a linear relationship between MQI_total and MetS ($P_{overall} < 0.001$, $P_{non-linear} = 0.968$) (Fig. 2A). For the elevated waist circumference and elevated triglycerides, there were an approximate negative linear association between MQI_total and elevated waist circumference ($P_{overall} < 0.001$, $P_{non-linear} = 0.335$, Fig. 2B), as well as elevated triglycerides ($P_{overall} < 0.001$, $P_{non-linear} = 0.356$, Fig. 2C). For the other components, there were non-linear association between MQI_total and hypertension ($P_{overall} < 0.001$, $P_{non-linear} = 0.035$, Fig. 2D), elevated fasting glucose ($P_{overall} < 0.001$, $P_{non-linear} = 0.029$, Fig. 2E), reduced HDL-C ($P_{overall} < 0.001$, $P_{non-linear} = 0.028$, Fig. 2F).

Table 3 presents the results of subgroup analyses based on various factors, including age, gender, race, educational level, marital status, PIR, smoking status, drinking status, physical activity, hypertension, diabetes, energy intake, HbA1c, ALT, AST, creatinine, uric acid, and total cholesterol. Notably, significant differences were observed with respect to creatinine levels and total cholesterol (P for interaction = 0.01 and 0.04, respectively), suggesting that creatinine and cholesterol play a moderating role in the relationship between MQI_total and MetS. The results suggested that MQI may have exerted a stronger protective effect against MetS in populations with lower creatinine and cholesterol levels compared to those with higher levels. No significant interactions were found in other subgroup analyses (all P for interaction > 0.05).

Considering the different diagnostic criteria for MetS, we conducted a sensitivity analysis using the IDF criteria to diagnose MetS (Supplementary Table S3). In Model 1 (with no covariates included), MQI_total was negatively associated with MetS (OR = 0.37, 95% CI: 0.33–0.42, $P < 0.0001$). After adjusting for relevant covariates, a negative association persisted in both Model 2 (OR = 0.36, 95% CI, 0.31–0.41, $P < 0.0001$) and Model 3 (OR = 0.53, 95% CI: 0.36–0.77, $P = 0.02$).

Discussion

To our knowledge, this is the first study to examine the relationship between comprehensive muscle quality, as assessed by the MQI, and MetS. Our findings revealed that low MQI was associated with an increased risk of MetS, and MQI showed a negative association with MetS components, including elevated waist circumference, hypertension, elevated fasting glucose, reduced serum HDL cholesterol, and elevated serum triglycerides. Subgroup and sensitivity analyses yielded robust results.

Previous studies have partially explored the relationship between muscle mass and MetS. For instance, Kim et al. found a strong correlation between reduced muscle mass and MetS, with each quartile increase in appendicular

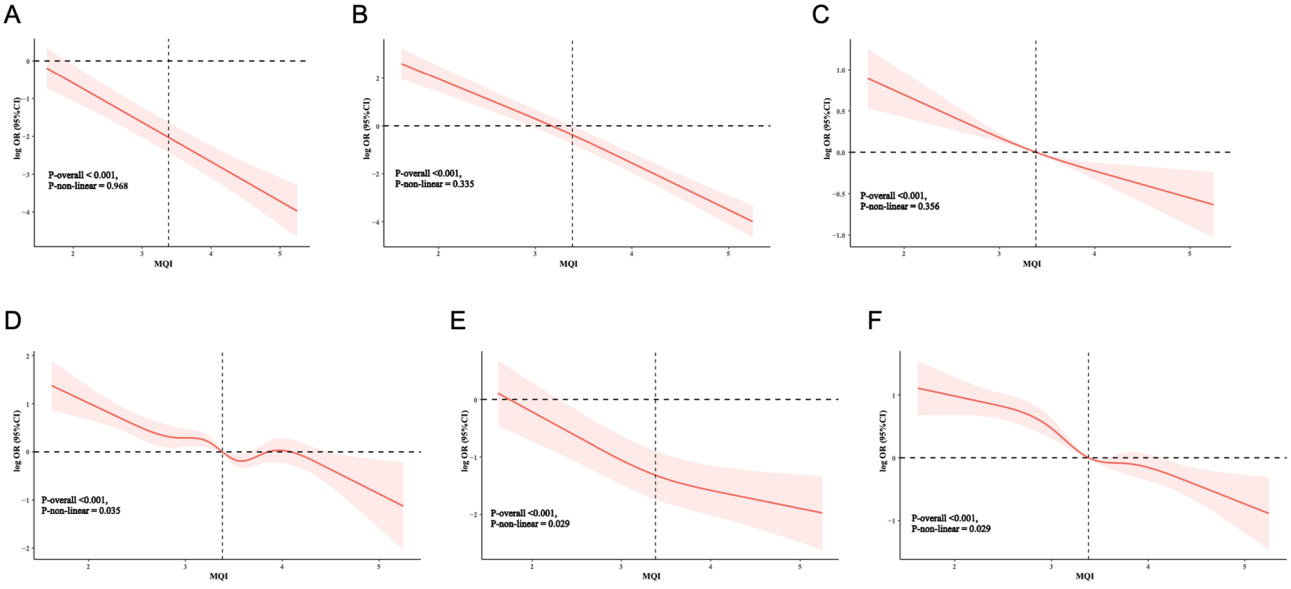

Fig. 2 The relationships between muscle quality index and the risk of metabolic syndrome (**A**), as well as its components—elevated waist circumference (**B**), elevated TGs (**C**), hypertension (**D**), elevated fasting glucose (**E**), and reduced HDL-C (**F**) using restricted cubic splines. The restricted cubic splines model was adjusted for age, gender, ethnicity, educational level, marital status, PIR, smoking status, drinking status, METs, energy intake, uric acid levels, AST levels, ALT levels. Abbreviations: MQI, muscle quality index; MetS, metabolic syndrome; HDL-C, high density lipoprotein cholesterol; TGs, triglycerides; PIR, poverty income ratio; METs, metabolic equivalent of tasks; AST, aspartate aminotransferase; ALT, alanine aminotransferase

Table 3 Subgroup and interaction analyses of the association between muscle quality index and metabolic syndrome

Variables	OR (95% CI)	*P* value	*P* for interaction
Age, years			0.23
< 50	0.57 (0.44, 0.74)	< 0.001	
≥ 50	0.97 (0.62, 1.52)	0.70	
Gender, %			0.16
Male	0.46 (0.26, 0.83)	0.02	
Female	0.51 (0.36, 0.72)	0.01	
Race, %			0.34
Non-Hispanic White	0.52 (0.35, 0.76)	0.01	
Mexican American	0.33 (0.22, 0.51)	< 0.001	
Non-Hispanic Black	0.55 (0.30, 1.00)	0.05	
Others	0.38 (0.22, 0.66)	0.01	
Educational levels, %			0.83
Above high school	0.47 (0.30, 0.72)	0.01	
High school	0.64 (0.30, 1.35)	0.15	
Below high school	0.37 (0.23, 0.61)	0.01	
Marital status, %			0.09
Never married	0.34 (0.19, 0.59)	0.01	
Divorced/Seperated/Widowed	0.48 (0.21, 1.12)	0.07	
Married/Living with partner	0.53 (0.36, 0.76)	0.01	
PIR, %			0.66
Q1 (< 1.3)	0.40 (0.26, 0.61)	0.004	
Q2 (1.3–3.5)	0.49 (0.30, 0.80)	0.01	
Q3 (> 3.5)	0.50 (0.32, 0.78)	0.01	
Smoking status, %			0.61
Never	0.57 (0.38, 0.85)	0.01	
Former	0.61 (0.33, 1.13)	0.10	
Now	0.30 (0.20, 0.47)	< 0.001	
Drinking status, %			0.98
Former	0.33 (0.18, 0.61)	0.003	
Never	0.79 (0.35, 1.74)	0.50	
Mild	0.56 (0.34, 0.93)	0.03	
Moderate	0.69 (0.39, 1.23)	0.18	
Heavy	0.29 (0.19, 0.44)	< 0.001	
METs, minute/week			0.99
Q1 (< 360)	0.53 (0.38, 0.75)	0.004	
Q2 (360–3600)	0.60 (0.42, 0.84)	0.01	
Q3 (> 3600)	0.35 (0.19, 0.61)	0.004	
Hypertension			0.09
No	0.50 (0.37, 0.67)	0.001	
Yes	0.49 (0.34, 0.71)	0.004	
Hyperlipidemia			0.13
No	0.32 (0.13, 0.77)	0.02	
Yes	0.50 (0.38, 0.66)	< 0.001	
Diabetes			0.45
No	0.50 (0.39, 0.64)	< 0.001	
Yes	0.30 (0.10, 0.84)	0.03	
Energy intake, kcal/day			0.34
Q1 (< 1727.0)	0.56 (0.39, 0.79)	0.01	
Q2 (1727.0-2526.0)	0.53 (0.38, 0.76)	0.005	
Q3 (> 2526.0)	0.34 (0.20, 0.59)	0.003	
HbA1c, %			0.94
Q1 (< 18.0)	0.18 (0.13, 0.23)	< 0.001	
Q2 (18.0–26.0)	0.20 (0.15, 0.26)	< 0.001	

Table 3 (continued)

Variables	OR (95% CI)	*P* value	*P* for interaction
Q3 (> 26.0)	0.15 (0.10, 0.23)	< 0.001	
ALT			0.47
Q1 (< 18.0)	0.41 (0.28, 0.60)	0.002	
Q2 (18.0–26.0)	0.48 (0.27, 0.86)	0.02	
Q3 (> 26.0)	0.52 (0.38, 0.72)	0.004	
AST			0.15
Q1 (< 20.0)	0.39 (0.26, 0.56)	0.001	
Q2 (20.0–25.0)	0.56 (0.34, 0.92)	0.03	
Q3 (> 25.0)	0.52 (0.33, 0.82)	0.01	
Creatinine, μmol/L			0.01
Q1 (< 66.3)	0.41 (0.28, 0.58)	0.001	
Q2 (66.3–82.2)	0.53 (0.30, 0.92)	0.03	
Q3 (> 82.2)	0.56 (0.33, 0.95)	0.04	
Uric acid, μmol/L			0.77
Q1 (< 279.6)	0.42 (0.27, 0.67)	0.004	
Q2 (279.6-350.9)	0.56 (0.42, 0.74)	0.002	
Q3 (> 350.9)	0.44 (0.30,0.65)	0.002	
Total cholesterol, mmol/L			0.04
Q1 (< 4.4)	0.44 (0.22, 0.86)	0.02	
Q2 (4.4–5.3)	0.43 (0.26, 0.71)	0.01	
Q3 (> 5.3)	0.57 (0.38, 0.84)	0.01	

Abbreviations: MetS, metabolic syndrome; PIR, poverty income ratio; METs, metabolic equivalent of task; HbA1c, glycated hemoglobin; ALT, alanine aminotransferase; AST, aspartate aminotransferase; OR, odd ratio; CI, confidence interval

skeletal mass percentage (ASM%) lowering the risk of MetS by 56% [29]. Another large retrospective cohort study with a 7-year follow-up showed that individuals with a skeleton mass index (SMI) increase of 0–1% and > 1% had a lower risk of MetS (0.87 and 0.67, respectively) compared to those with SMI changes of < 0%[30]. Additional studies have reported a negative association between relative skeletal muscle mass (SMM) ratios (such as the skeletal muscle-to-visceral fat ratio [SVR] and the muscle-to-fat ratio [MFR]) and MetS [21]. Handgrip strength, a critical indicator of muscle mass, is closely related to disease prognosis [31]and prior research has also linked handgrip strength with MetS [32, 33]. Our findings are consistent with these previous studies. Moreover, a growing body of research on the association between sarcopenia and MetS supports the idea that declining muscle mass is a key contributor to MetS [20, 34, 35].

Skeletal muscles play a crucial role in glucose metabolism, accounting for up to 85% of insulin-mediated glucose uptake [36]. One characteristic of MetS is insulin resistance, and changes in skeletal muscle insulin resistance and glucose metabolism may be significant factors in the development of MetS [37]. Skeletal muscle negatively affects its own insulin resistance and lipid metabolism through mechanisms such as oxidative stress, inflammatory cytokines, and mitochondrial dysfunction [38]. Petersen et al. found that young, lean individuals with insulin resistance (IR) had higher intramuscular lipid content, reduced muscle glycogen synthesis by 61%, and a 2.2-fold increase in hepatic de novo lipogenesis compared to non-IR individuals, leading to elevated plasma triglycerides and decreased HDL levels. This suggests that lipid metabolism disorders are one of the causes of insulin resistance [39].

The distribution and metabolism of adipose tissue in the body are often accompanied by changes in muscle mass and quantity, as well as changes in the risk of metabolic syndrome. With aging, changes in fat distribution and proportion affect skeletal muscle mass. Brown adipose tissue and white adipose tissue play roles in energy storage and energy expenditure, respectively [40]. After age 40, brown adipose tissue decreases, reducing fat consumption, which leads to fat accumulation and triggers MetS [41]. Studies have shown that the accumulation of visceral fat (central obesity) can increase the risk of insulin resistance and metabolic diseases, while subcutaneous fat (such as fat in the buttocks and flanks) has no adverse effects and may even reduce the risk of metabolic syndrome [42, 43]. Experimental studies on rodents have also shown that subcutaneous transplantation of white adipose tissue can improve glucose metabolism in the body [44]. At the genetic level, subcutaneous adipocytes themselves have high levels of short status homeobox 2 (Shox2) and glypican-4 (GPC4), which protect against metabolic syndrome by inhibiting fat breakdown and maintaining insulin sensitivity [45, 46]; however, visceral adipose tissue exhibits high levels of HoxC8 and HoxA5 expression, which are detrimental to the stability of

metabolic levels in the body by regulating fat browning and deposition [47, 48].

Inflammation is another pathway leading to MetS. Skeletal muscle produces irisin and interleukin-6 (IL-6) during metabolism, which are critical for maintaining insulin resistance and glucose homeostasis [49, 50] Previous human studies have shown compensatory increases in irisin levels in the blood of MetS patients [51]. Animal studies indicated that irisin induces the browning of white adipocytes, improving insulin sensitivity and glucose tolerance [52]. IL-6 can activate anti-obesity and insulin-sensitizing pathways, such as AMPK and insulin signaling, via the glycoprotein 130 (gp130) receptor in skeletal muscle, enhancing glucose uptake [53, 54]. Corticosteroids are also one of the main regulatory factors in the inflammatory response process in the body [55]. Studies have found that there are glucocorticoid receptors in skeletal muscles, and the glucocorticoid level in vivo is also related to the functional changes of skeletal muscle [56]. The expression of glucocorticoid receptor A in skeletal muscle cells of patients with metabolic syndrome increases, up regulates the expression of 11-b-hydroxysteroid dehydrogenase isoform 1, further reduces the sensitivity of glucocorticoids and enhances insulin resistance [57].

Additionally, mitochondrial function and activity changes in skeletal muscle are key in the development of MetS. Studies by Befroy and Morino et al. have shown that although offspring of type 2 diabetes patients have normal insulin resistance, reduced mitochondrial content impairs oxidative phosphorylation, leading to decreased lipid oxidation and the accumulation of lipid metabolites, which trigger MetS [58, 59].

Strengths and limitations

This study has several strengths. First, it is the first to use nationally representative NHANES data to analyze the association between MQI and MetS in U.S. adults. Second, the MQI combines both handgrip strength and appendicular skeletal muscle mass, providing a comprehensive measure of muscle quality while considering racial differences in the U.S. population. Third, by incorporating a broad range of covariates related to blood biochemistry, nutrition, and lifestyle behaviors, the study effectively minimized potential biases. Fourth, since our study population consisted of U.S. adults aged 20–60 years, we adopted the NCEP ATP III criteria to define MetS, which are widely used in epidemiological studies. However, considering that the IDF-2009 criteria place greater emphasis on ethnic and regional differences, particularly with regard to waist circumference thresholds, we included MetS defined by the IDF-2009 criteria in a sensitivity analysis. Despite these strengths, the study has some limitations. First, this study is a cross-sectional analysis, which limits our ability to establish causal relationships between MQI and MetS, highlighting the need for future longitudinal cohort studies. Second, variations in the diagnostic criteria for MetS across different racial and regional populations indicate that further research is necessary to investigate the association between MQI and MetS in more diverse populations. Third, although we adjusted for as many accessible covariates as possible, the possibility of residual confounding cannot be excluded, as unmeasured variables may still affect the observed association. Lastly, existing evidence suggests a potential bidirectional relationship between MetS and muscle mass, underscoring the need for future studies to elucidate the underlying physiological and biochemical mechanisms.

Conclusion

Low muscle quality, as assessed by the MQI, is significantly associated with the risk of MetS, showing a linear dose-response relationship. Therefore, improving muscle quality could serve as a promising and effective intervention for the prevention of MetS.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13098-025-01766-w.

Supplementary Material 1

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Author contributions

WC, writing-original draft (lead), formal analysis (equal), methodology (lead); DBC, formal analysis (lead), writing-original draft (equal), methodology (equal); YZZ, writing-review and editing (lead), writing-original draft (equal), methodology (equal); LYX, methodology (equal), writing-review and editing (equal); YJW, methodology (equal), writing-review and editing (equal); YLC, conceptualization (equal), writing-review and editing (lead), supervision (lead); YNL, conceptualization (lead), writing-review and editing (lead), supervision (lead); JHZ, conceptualization (lead), writing-review and editing (lead), supervision (lead), methodology (lead). All authors critically reviewed the manuscript for important intellectual content. JHZ, YNL and YLC are the study guarantor. The corresponding author attests that all listed authors meet authorship criteria and that no others meeting the criteria have been omitted.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethical approval

The NHANES protocol was approved by the National Center for Health Statistics Research Ethics Review Board, and all NHANES participants had signed informed consent. Therefore, access to NHANES database does not require any ethical or administrative permission. More information is available at the website (www.cdc.gov/nchs/nhanes/ accessed on 31 December 2024).

Competing interests

The authors declare no competing interests.

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