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Relative Grip Strength and Muscle-Strengthening Activity: Independent and Joint Associations with Type 2 Diabetes Mellitus

Yunmin Han, Yeon Soo Kim*
Department of Physical Education, Seoul National University, Seoul, Korea

Background: Grip strength and muscle-strengthening activity (MSA) have been independently associated with type 2 diabetes mellitus (T2DM). However, analyses that consider grip strength in conjunction with MSA, while factoring in age and sex as well, are limited. Therefore, we aimed to investigate the association of relative grip strength (RGS) and MSA, separately and in combination, with T2DM, considering differences in age and sex.
Methods: A total of 27,702 participants aged 19 years and older were included from 2014 to 2021 from the Korea National Health and Nutrition Examination Survey. The association between RGS, MSA, and T2DM was assessed using logistic regression analysis. Odds ratios (OR) and 95% confidence intervals (CI) were calculated for the independent and joint associations of RGS and MSA on T2DM prevalence.
Results: Highest (Q4) RGS levels were independently associated with lower odds of T2DM (OR, 0.39; 95% CI, 0.32 to 0.46; *P* for trend <0.001). Similarly, engaging in MSA 2 o 3 days per week was associated with lower odds of T2DM (OR, 0.80; 95% CI, 0.66 to 0.96), although the trend was not statistically significant (*P* for trend=0.775). In the joint analysis, participants with normal RGS and engaging in MSA ≥2 days per week had the lowest odds of T2DM (OR, 0.60; 95% CI, 0.51 to 0.70).
Conclusion: Higher RGS and engaging in MSA 2 to 3 days per week are independently associated with lower likelihood of T2DM. The combined association of normal RGS and MSA 2 days or more per week shows the greatest benefit for T2DM prevention.

Key words: Hand strength, Resistance training, Type 2 Diabetes mellitus, Health behavior, Primary prevention

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*Corresponding author
Yeon Soo Kim

https://orcid.org/0000-0003-1447-0196

Department of Physical Education, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 08826, Korea
Tel: +82-2-880-7804
E-mail: kys0101@snu.ac.kr

INTRODUCTION

Type 2 diabetes mellitus (T2DM) is a global public health problem and a leading cause of mortality and decreased life expectancy, with the number of affected individuals increasing annually.[1] Global trends show an increase in the prevalence of T2DM among young people.[2] As of 2021, 68.5% of individuals with T2DM are adults under the age of 70 in Korea, and the rising prevalence of T2DM in children, youth, and middle-aged adults poses a significant social burden.[3,4] Additionally, while T2DM prevalence is higher in males, who are also diagnosed at younger ages, females experience higher rates of cardiovascular disease (CVD) and mortality related to T2DM.[5] Therefore, it is crucial to analyze prevention strategies for T2DM through an approach that is specific to age and sex.

Grip strength, considered an indicator of total muscle strength, is widely recognized as a tool to predict mortality and the presence of various chronic diseases.[6] Low levels of grip strength are associated with a higher risk of CVDs and other chronic conditions.[7,8] Previous observational studies have demonstrated an association between grip strength and the prevalence of T2DM, suggesting that stron-

ger grip strength may reduce the risk of this metabolic disorder.[9-11] However, most previous studies have primarily categorized participants based on absolute grip strength, with limited research dividing subjects by age group. Relative grip strength (RGS) is proposed as a method to overcome the confounding of strength measurements by body mass and to address the health implications of higher body weight and reduced muscle strength.[12] This measure accounts for individual variations in body size, providing a more accurate reflection of muscular health's impact on chronic disease risk and mortality. Therefore, RGS may serve as a more significant indicator compared to absolute grip strength for predicting the risk of T2DM and establishing associations.[13,14]

Muscle-strengthening activity (MSA) is known to enhance insulin sensitivity and improve glucose regulation, thereby reducing the risk for and aiding in the prevention of T2DM.[15] Therefore, most physical activity guidelines recommend engaging in MSA at least twice a week for the prevention of non-communicable diseases.[16,17] Current epidemiologic evidence suggests that engagement in MSA over one to two sessions per week (or approximately 30 to 150 minutes) was associated with reduced risk of CVD, T2DM, and all-cause mortality.[18-20] However, most prior studies have predominantly involved Caucasian populations, including only a limited number of participants from other ethnicities, and have not focused extensively on gender and age-specific differences. Additionally, to our knowledge, no studies have examined the joint association of grip strength and MSA on the prevalence of T2DM.

Therefore, this study aimed to investigate the independent and joint associations of RGS and MSA with T2DM. Furthermore, it aimed to explore the differences in T2DM based on age and sex.

METHODS

Study populations

The Korea National Health and Nutritional Examination Survey (KNHANES) is an annual nationwide survey carried out by the Korea Disease Control and Prevention Agency. This survey gathers information on the health, behaviors, and nutritional status of Koreans, serving as a tool to oversee the health conditions of the Korean population. The data from the 6th to 8th cycles of the KNHANES, which encompass the years 2014 to 2019, included 37,916 individuals aged 19 years and older as participants. The final analysis excluded individuals who could not be assessed for diabetes status (n = 3,650), those without available grip strength data (n = 1,933), participants with unknown days of MSA (n = 171), and those missing covariates (n = 4,460), resulting in a total of 27,702 participants for the final analysis.

The Institutional Review Board (IRB) of Seoul National University approved this study (IRB NO. E2404/004-008) and waived the requirement for informed consent due to the use of de-identified data.

Definition of T2DM

In this study, T2DM was the primary dependent variable. Blood samples were taken after fasting for 8 hours and then sent to a central laboratory for analysis within 24 hours. Fasting plasma glucose was measured with the Hitachi 7600 Automatic Analyzer (Hitachi), and glycosylated hemoglobin (HbA1c) levels were assessed using the G8 automated high-performance liquid chromatography system (Tosoh). T2DM was identified based on the existence of any of the following conditions: (1) fasting plasma glucose level ≥ 126 mg/dL, (2) HbA1c level ≥ 6.5%, or (3) current use of any antidiabetic medication.

Exposures

Grip strength was measured using a digital grip strength dynamometer (T.K.K 5401; TAKEI). The individual grip strength value was determined by taking the highest value from three measurements of grip strength in both hands, focusing on the hand that is primarily used. RGS was calculated by dividing the absolute grip strength by body mass index (BMI), and it was categorized into sex-specific quartiles.[21,22] The analysis was conducted based on these quartile groups.

The frequency of MSA (e.g., push-ups, sit-ups, dumbbells, or barbell exercises) was assessed by asking participants how many days per week they performed any MSA. MSA was categorized into groups of 0, 1, 2–3, and more than 4 days. The World Health Organization (WHO) recommends that adults perform MSA that works for all major muscle groups on 2 or more days a week.[16] Therefore, sufficient MSA was defined as 2 or more days per week, and grip strength was defined as low for the lowest RGS quartile (Q1) and

normal for the remaining RGS quartiles.[23] The variable that combined RGS and MSA was categorized into four groups: (1) low RGS and not meeting MSA recommended levels, (2) low RGS and meeting MSA recommended levels, (3) normal RGS and not meeting MSA recommended levels, and (4) normal RGS and meeting MSA recommended levels.

Covariates

Sociodemographic factors included age, sex (male and female), household income (low, mid-low, mid-high, and high), educational level (< high school, high school graduate, and ≥ college), and family history of diabetes (yes or no). BMI was calculated as weight in kilograms divided by the square of height in meters. Smoking status was ascertained through self-reported information regarding current smoking habits (smoker or non-smoker). Alcohol consumption was evaluated by surveying participants on their usual weekly intake of alcoholic beverages. Heavy drinking was categorized as exceeding seven drinks per week for males and five drinks per week for females.[24] Physical activity was measured using the Global Physical Activity Questionnaire, which evaluates the intensity, duration, and frequency of aerobic activities across work, transport, and leisure domains.[25] Participants were classified as meeting or not meeting the WHO physical activity guidelines, which recommend at least 150 minutes of moderate to vigorous activity per week for adults, based on their self-reported physical activity levels.[16] Hypertension was identified in individuals with a systolic blood pressure of ≥ 140 mmHg, a diastolic blood pressure of ≥ 90 mmHg, or those on medication for hypertension.[26] Criteria for dyslipidemia included a total cholesterol level of ≥ 240 mg/dL, a low-density lipoprotein cholesterol level of ≥ 160 mg/dL, a high-density lipoprotein cholesterol level of < 40 mg/dL for males and < 50 mg/dL for females, triglycerides of ≥ 200 mg/dL, or the use of lipid-lowering medications.[27]

Statistical analysis

Considering the stratified, multistage probability, and sampling design of KNHANES, survey-weighted analyses were performed to ensure representativeness. Participants' characteristics were presented as mean ± standard error (SE) for continuous variables and as proportion ± SE for categorical variables. Group comparisons were conducted using survey-weighted generalized linear models for continuous data and the Rao-Scott F-adjusted chi-square test for categorical data.

The weighted logistic regression analysis was used to calculate odds ratios (OR) and 95% confidence intervals (CI), investigating the relationship between RGS and MSA with T2DM. To examine the associations of various covariates on the relationship between RGS and MSA with T2DM, adjustments for these factors were incorporated into the analysis: model 1, age and sex; model 2, model 1+education, income, current smoking, heavy drinking, RGS (when MSA is the main exposure), and MSA (when RGS is the main exposure); and model 3, model 2+hypertension, dyslipidemia, family history of diabetes, and BMI (when MSA is the main exposure).

To assess the joint association of RGS and MSA with T2DM, we categorized participants into four groups based on their RGS levels and whether they met the MSA guidelines: (1) low RGS and not meeting MSA guidelines, (2) low RGS and meeting MSA guidelines, (3) normal RGS and not meeting MSA guidelines, and (4) normal RGS and meeting MSA guidelines.

In addition, we assessed potential effect modification by age and sex by including interaction terms between age groups (< 65 years vs. ≥ 65 years) and sex (male vs. female) in our multivariable regression models. Interaction effects were evaluated using Wald tests, and the overall significance level for the analysis was set at *P*-value <0.05. All statistical analyses were performed using Stata version 17.0 (StataCorp.).

RESULTS

Among the 27,702 participants, 3,410 were diagnosed with T2DM. The prevalence of T2DM was 7.8% among participants under the age of 65 and 26.6% among those aged 65 and above. Furthermore, the prevalence was higher among males at 11.7%, compared to females at 8.6%. Table 1 presents the baseline characteristics according to T2DM status. Compared to those without T2DM, individuals with T2DM were more likely to be male, older, have higher BMI, lower levels of physical activity, and a higher prevalence of hypertension and dyslipidemia.

Compared to lower RGS levels, higher RGS levels were significantly associated with lower OR values for T2DM prevalence (*P*

Table 1. Baseline characteristics of the study participants by T2DM status

Characteristic	Overall	Non-T2DM	T2DM	*P*
Unweighted number	27,702	24,292	3,410	
Female sex (%)	49.2±0.3	50.1±0.3	41.4±0.9	<0.001
Age (yr)	45.3±0.2	43.9±0.2	58.6±0.3	<0.001
Height (cm)	165.3±0.1	165.5±0.1	163.6±0.2	<0.001
Weight (kg)	65.5±0.1	65.1±0.1	69.2±0.3	<0.001
Education level (%)				<0.001
<High school	19.5±0.4	16.9±0.4	43.2±1.1	
High school graduate	37.2±0.4	37.7±0.5	37.8±0.4	
≥College	43.3±0.6	45.5±0.6	24.0±1.0	
Household income (%)				<0.001
Low	13.0±0.4	11.6±0.3	25.3±0.9	
Mid-Low	23.7±0.5	23.3±0.5	27.1±0.9	
Mid-High	30.2±0.4	30.9±0.5	24.5±1.0	
High	33.1±0.6	34.3±0.7	22.9±0.9	
Body mass index (kg/m^2)	23.9±0.03	23.6±0.03	25.7±0.1	<0.001
Current smoker (%)	22.0±0.3	21.8±0.4	23.7±0.9	0.034
Heavy drinking (%)*	13.1±0.3	12.8±0.3	16.1±0.8	<0.001
Physically active (%)†	49.8±0.4	50.8±0.4	40.5±1.0	<0.001
Muscle-strengthening activity (%)‡	22.8±0.3	23.2±0.3	18.7±0.8	<0.001
Absolute grip strength (kg)	32.9±0.1	33.1±0.1	31.9±0.2	<0.001
Hypertension (%)	24.1±0.4	20.5±0.3	56.4±1.0	<0.001
Dyslipidemia (%)	47.0±0.4	43.6±0.4	76.3±0.8	<0.001
Family history of diabetes (%)	20.5±0.3	19.3±0.3	31.8±1.0	<0.001

Values are presented as weighted mean±standard error.
*Seven drinks per week for males and five for females; †Engaged in moderate to vigorous physical activity for more than 150 minutes per week; ‡Performed at least twice a week.
T2DM, type 2 diabetes mellitus.

for trend <0.001). In terms of the association between the number of MSA days and T2DM prevalence, only the group that performed exercises 2 to 3 days a week showed a significantly lower OR value compared to those who did not perform any exercise per week. In the adjusted model, no significant associations were observed for groups that performed exercises less than 2 days or more than 4 days per week (Table 2).

In analyses stratified by age group, higher levels of RGS were associated with a lower prevalence of T2DM in both groups. In the group under 65 years of age, compared to the lowest quartile of grip strength, the OR with 95% CI for the second, third, and fourth quartiles were 0.70 (95% CI, 0.60 to 0.81), 0.54 (95% CI, 0.46 to 0.64), and 0.35 (95% CI, 0.28 to 0.43), respectively. In the female group, according to RGS levels, compared to the lowest quartile, the OR for T2DM with 95% CI were 0.73 (95% CI, 0.62 to 0.87), 0.58 (95% CI, 0.47 to 0.70), and 0.38 (95% CI, 0.29 to 0.49) for the second, third, and fourth quartiles, respectively. Additionally, significant interaction effects were observed only in the RGS group stratified by age (<65 years vs. ≥65 years) (*P* for interaction <0.001).

An association between MSA levels and T2DM was observed only in the group aged 65 and older. Compared to those who did not engage in any MSA, the group practicing 1 day per week had an OR of 0.58 (95% CI, 0.29 to 1.14), while those practicing 2 to 3 days per week showed an OR of 0.61 (95% CI, 0.43 to 0.86). In the sex-specific analysis, only the male group practicing 2 to 3 days per week exhibited a significant association, with an OR of 0.71 (95% CI, 0.56 to 0.89) compared to those who did not engage in any MSA (Table 3).

To perform a joint analysis, we examined the interaction between RGS and MSA, finding no significant interaction (*P*=0.679). The joint analysis showed no significant association for groups with low RGS engaging in MSA compared to those with low RGS who do

Table 2. Odds ratio for type 2 diabetes mellitus by relative grip strength and muscle-strengthening activity levels

	Model 1	Model 2	Model 3
Relative grip strength*			
Q1	1 (Reference)	1 (Reference)	1 (Reference)
Q2	0.74 (0.66–0.83)	0.75 (0.67–0.84)	0.79 (0.70–0.88)
Q3	0.56 (0.50–0.64)	0.57 (0.50–0.65)	0.64 (0.56–0.73)
Q4	0.31 (0.26–0.36)	0.31 (0.26–0.37)	0.39 (0.32–0.46)
P for trend	< 0.001	< 0.001	< 0.001
Per 1-SD	0.59 (0.56–0.63)	0.59 (0.55–0.63)	0.64 (0.60–0.69)
Muscle-strengthening activity†			
0 day/wk	1 (Reference)	1 (Reference)	1 (Reference)
1 day/wk	0.84 (0.63–1.11)	0.96 (0.72–1.27)	1.01 (0.76–1.36)
2–3 day/wk	0.66 (0.55–0.78)	0.75 (0.62–0.89)	0.80 (0.66–0.96)
≥ 4 day/wk	0.83 (0.72–0.96)	0.96 (0.82–1.11)	1.02 (0.87–1.20)
P for trend	< 0.001	0.208	0.775

Regarding relative grip strength, 1 SD change is equivalent to 0.13 kg. Model 1: Adjusted for age and sex; Model 2: Adjusted for model 1 plus household income, education, smoking status, heavy drinking, physical activity, relative grip strength (when muscle-strengthening activity is the main exposure), and muscle-strengthening activity (when relative grip strength is the main exposure).
*Model 3: Adjusted for model 2 plus hypertension, dyslipidemia, and family history of diabetes; †Model 3: Adjusted for model 2 plus hypertension, dyslipidemia, family history of diabetes, and body mass index.
SD, standard deviation.

Table 3. Odds ratios for type 2 diabetes mellitus by relative grip strength and muscle-strengthening activity levels stratified by age and sex

	Full adjusted model			
	Age (yr)		Sex	
	< 65	≥ 65	Male	Female
Relative grip strength*				
Q1	1 (Reference)	1 (Reference)	1 (Reference)	1 (Reference)
Q2	0.70 (0.60–0.81)	0.74 (0.61–0.90)	0.83 (0.70–0.97)	0.73 (0.62–0.87)
Q3	0.54 (0.46–0.64)	0.65 (0.53–0.79)	0.69 (0.57–0.82)	0.58 (0.47–0.70)
Q4	0.35 (0.28–0.43)	0.56 (0.43–0.67)	0.40 (0.32–0.50)	0.38 (0.29–0.49)
P for trend	< 0.001	< 0.001	< 0.001	< 0.001
Per 1-SD	0.59 (0.55–0.64)	0.74 (0.68–0.81)	0.72 (0.67–0.77)	0.69 (0.64–0.75)
P for interaction	< 0.001		0.582	
Muscle-strengthening activity†				
0 day/wk	1 (Reference)	1 (Reference)	1 (Reference)	1 (Reference)
1 day/wk	1.09 (0.79–1.51)	0.58 (0.29–1.14)	1.06 (0.75–1.50)	0.91 (0.55–1.49)
2–3 day/wk	0.85 (0.69–1.06)	0.61 (0.43–0.86)	0.71 (0.56–0.89)	1.09 (0.80–1.48)
≥ 4 day/wk	1.05 (0.85–1.30)	0.97 (0.78–1.22)	1.05 (0.87–1.27)	0.90 (0.67–1.22)
P for trend	0.922	0.251	0.954	0.987
P for interaction	0.731		0.135	

Regarding relative grip strength, 1 SD change is equivalent to 0.12 kg for the age-stratified group, 0.11 kg for males, and 0.09 kg for females.
*Adjusted for age, sex, household income, education, smoking status, heavy drinking, physical activity, hypertension, dyslipidemia, family history of diabetes, and muscle-strengthening activity; †Adjusted for age, sex, household income, education, smoking status, heavy drinking, physical activity, hypertension, dyslipidemia, family history of diabetes, body mass index, and relative grip strength.
SD, standard deviation.

not engage in MSA. However, a significantly lower OR for T2DM prevalence was observed in the normal grip strength group, at 0.60 (95% CI, 0.51 to 0.70), particularly among those adhering to MSA recommendations (Fig. 1). Additionally, the age and sex-stratified

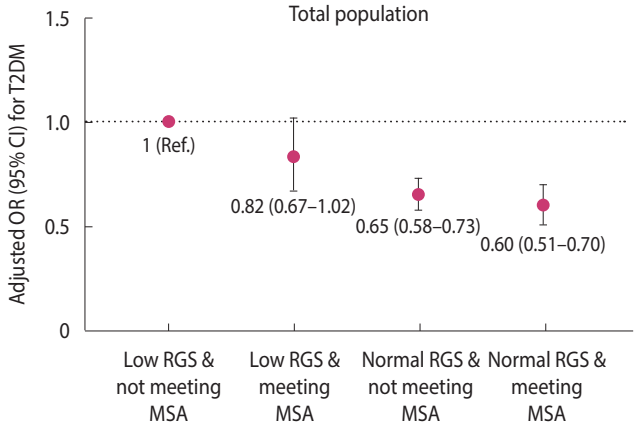

Figure 1. Joint association of relative grip strength and muscle-strengthening activity (MSA) with type 2 diabetes mellitus (T2DM). Low relative grip strength (RGS) represents the lowest quartile, while normal RGS comprises the remaining quartiles. MSA criteria are defined by the engagement of muscle-strengthening exercises at least twice per week. The full model is adjusted for age, sex, household income, education, smoking status, heavy drinking, physical activity, hypertension, dyslipidemia, and family history of diabetes. OR, odds ratio; CI, confidence interval.

analysis showed similar trends to those observed in the total population (Fig. 2). However, among individuals under the age of 65 and females, those with normal RGS and who met the MSA recommendations exhibited a lower association with T2DM compared to their counterparts.

DISCUSSION

This study investigated the association between RGS and MSA with T2DM prevalence. Our findings demonstrate that higher RGS is significantly associated with a lower prevalence of T2DM. This association was more pronounced among younger participants and females. Additionally, engaging in MSA 2 to 3 days per week was associated with a lower prevalence of T2DM compared to no participation in MSA. A significant association between sufficient MSA and lower T2DM prevalence was also observed among individuals with lower grip strength, particularly older adults. This association

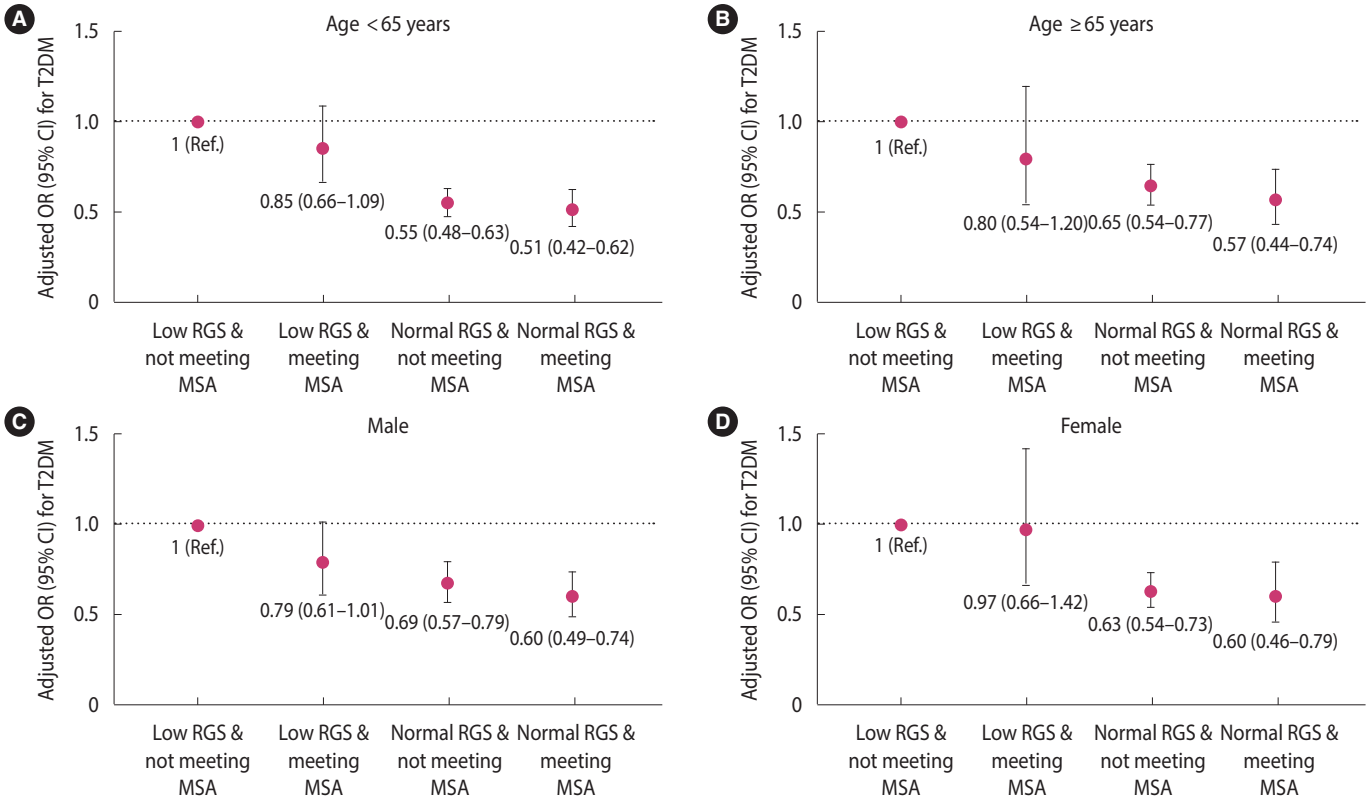

Figure 2. Joint association of relative grip strength and muscle-strengthening activity (MSA) with type 2 diabetes mellitus (T2DM) by sex and age-stratified group. The figure shows each group: (A) age <65 years, (B) age ≥65 years, (C) male, and (D) female. Low relative grip strength (RGS) represents the lowest quartile, while normal RGS comprises the remaining quartiles. MSA criteria are defined by the engagement of muscle-strengthening exercises at least twice per week. The full model is adjusted for age, sex, household income, education, smoking status, heavy drinking, physical activity, hypertension, dyslipidemia, and family history of diabetes. OR, odds ratio; CI, confidence interval.

was similarly evident in male participants. These findings suggest that the association between T2DM and various indicators varies depending on age and sex. In the joint analysis, the group with normal RGS and engaging in MSA at least twice a week demonstrated the lowest association with T2DM, compared to those with low RGS and fewer than 2 days of MSA practice per week.

Previous research conducted on a Korean population supports the findings that the group with the lowest RGS (Q1) exhibits a 2.7 times increase in the prevalence of T2DM among males and a 3.4 times increase among females, compared to the group with the highest grip strength (Q4).[11] Additionally, a meta-analysis based on prospective studies examining the overall risk of T2DM incidence associated with grip strength found that for absolute grip strength, each 5-kg increment resulted in a hazard ratio (HR) for T2DM incidence of 0.95 (95% CI, 0.92 to 0.96). In contrast, for RGS, each 0.1 increment showed a stronger association with an HR of 0.78 (95% CI, 0.71 to 0.86) for T2DM incidence.[14]

In a prospective cohort study, it was reported that engaging in MSA once or twice weekly (or approximately 60 to 150 minutes per week) could reduce the risk of T2DM by about 30%.[18] A meta-analysis examining the relationship between MSA and the risk of T2DM reported that engaging in such exercises for 60 minutes per week resulted in a relative risk of 0.83 (95% CI, 0.73 to 0.93), indicating a reduced risk compared to those who did not engage in these activities.[20]

Our research found that higher RGS levels are associated with a lower prevalence of T2DM. Interestingly, individuals who engaged in MSA 2 to 3 days per week showed a significantly lower prevalence of T2DM. In contrast, those performing MSA 4 or more days per week, despite having higher levels of overall physical activity, did not show a statistically significant association with T2DM. In our analysis, individuals who engaged in MSA 4 or more days per week tended to be older on average and have higher prevalence of hypertension and T2DM compared to those who engaged in 1 or 2–3 days MSA per week. This pattern may suggest that individuals with chronic conditions are more proactive in managing their health, which could have influenced the outcomes of our study.

Our analysis differentiated by age groups showed that individuals under 65 years of age demonstrated a stronger association between increased RGS levels and the reduced prevalence of T2DM. This suggests that enhanced muscle strength could be associated with lower T2DM prevalence in younger populations, highlighting a potential area for preventive measures. Conversely, among those aged 65 years and older, participating in MSA at least 2 to 3 days per week was associated with lower T2DM prevalence, suggesting that even modest MSA involvement could be linked to beneficial outcomes in T2DM prevalence among older adults. Although older adults experience a decline in strength associated with muscle mass loss, the reduction in strength occurs at a faster rate than the corresponding decrease in muscle mass, which indicates a deterioration in muscle quality.[28] Consequently, maintaining and enhancing muscle strength through targeted interventions is increasingly essential in the elderly population.

In the sex-specific analysis, while the association between RGS and T2DM prevalence showed similar patterns across genders, differences were observed in the association with MSA. This discrepancy may be further explained by sex differences in the decline of muscle function with age; notably, males experience more rapid declines in muscle strength, mass, and quality compared to females.[29,30] This emphasizes the importance of maintaining muscle strength, particularly in males. Furthermore, the extremely low engagement rate of MSA among females, where 85.6% did not participate in such activities even once per week, likely contributed to the observed lack of association between MSA and T2DM in this group. A previous study has shown these findings, revealing that in 2019, only 32.6% of Korean males engaged in MSA more than twice a week, compared to just 14.1% of females.[31]

Our joint analysis showed that the lowest association with T2DM is observed when RGS is normal and MSA is conducted more than twice a week. Similarly, age and sex-stratified analysis indicated that this trend is most pronounced in individuals under the age of 65 years. Given these findings, and considering that current public health guidelines recommend both males and females engage in MSA at least twice per week, it is imperative to design and implement interventions and policies that encourage regular participation in such activities across both genders.[16] This approach could prevent T2DM by enhancing muscle strength through consistent muscle-strengthening exercises.

Grip strength has been extensively studied in clinical and epidemiological research as a predictive marker for various diseases.[32]

Research has shown that higher grip strength is associated with a lower risk of cardiovascular events and reduced mortality rates.[33] These associations suggest that grip strength can be an accessible and cost-effective indicator of health risks across various populations. Resistance training aims to increase muscle mass, enhance muscle function, and improve metabolic health through adaptations such as increased muscle fiber size, altered muscle architecture, and enhanced neural activation.[34,35] These changes significantly improve muscular strength, thereby directly enhancing grip strength.

In terms of biological mechanisms, engaging in MSA is associated with reductions in adiposity and increases in muscle mass, which in turn lead to decreased levels of homeostasis model assessment for insulin resistance and C-peptide, thereby contributing to the prevention of T2DM.[18] Additionally, skeletal muscle has the ability to secrete a variety of peptides known as myokines, including myostatin, irisin, and myonectin.[36] These myokines have been identified as crucial for maintaining metabolic homeostasis.[37] Such metabolic substances significantly influence the body's metabolic processes and are likely key mediators in the relationship between MSA and improved metabolic health in T2DM.

To the best of our knowledge, no prior study has investigated the combined association of MSA and RGS with T2DM using national data. However, this study has several limitations. First, as this study is based on a cross-sectional design, causality between exposure factors and T2DM cannot be inferred. Second, the assessment of MSA levels in this study relied solely on self-reported data, recorded as the number of days per week engaged in such activities. This method of measurement is susceptible to measurement errors, potentially leading to inaccurate representations of actual activity levels. Third, despite adjustments for potential confounders, residual confounding may still exist due to unmeasured or unknown factors, such as calorie intake. Finally, while this study utilized national data to standardize the population, the exclusive inclusion of Korean participants limits its ability to accurately represent the other populations.

In conclusion, this is the first study to analyze the joint associations of RGS and MSA frequency on the prevalence of T2DM. Our findings suggested that higher levels of RGS are inversely associated with T2DM prevalence. Particularly, the lowest prevalence of T2DM was observed in individuals engaging in MSA 2 to 3 days per week. This association varied across different age and sex groups. In our joint analysis, participants with normal RGS who engaged in MSA at least twice a week had the lowest prevalence of T2DM compared to those with low RGS who engaged in MSA fewer than 2 days per week. These results suggest that maintaining normal RGS while adhering to regular MSA might be a practical strategy for screening and reducing the risk of developing T2DM. Future research should aim to measure MSA more objectively and validate these findings through longitudinal studies to establish causality more robustly.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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AUTHOR CONTRIBUTIONS

Study concept and design: YH and YSK; acquisition of data: YH; analysis and interpretation of data: YH and YSK; drafting of the manuscript: YH; critical revision of the manuscript: YSK; statistical analysis: YH; administrative, technical, or material support: YH and YSK; and study supervision: YSK.

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