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Higher abdominal adiposity is associated with higher lean muscle mass but lower muscle quality in middle-aged and older men and women: The Framingham Heart Study

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Abstract

Background: The objective was to determine if abdominal fat is related to poor muscle health.

Methods: This cross-sectional study included 428 males and 534 females with appendicular lean mass (ALM, kg) from dual energy x-ray absorptiometry (DXA), grip strength (kg), and upper extremity muscle “quality” (grip strength/arm lean mass) measured (1996-2001) in the Framingham Offspring Study. Sex-specific linear regressions associated adiposity measures [waist circumference (WC, cm) and visceral adipose tissue (VAT, cm^3), and subcutaneous adipose tissue (SAT, cm^3)] as Z-scores with each measure of muscle, adjusting for covariates. Models were further stratified by body mass index (BMI, <30, ≥30 kg/m^2).

Results: Mean (±SD) age was 60 ± 9 years and BMI was 28.9 ± 4.6 kg/m^2 (men) and 27.7 ± 5.8 kg/m^2, (women). In men, the BMI-stratified analyses showed higher WC was associated with higher ALM (P<0.0001 each) but with lower muscle quality (P<0.02) in both BMI groups. Higher SAT was also associated with higher ALM (P=0.0002) and lower muscle quality (P=0.0002) in men with BMI<30, but not in obese men. In women, higher WC, SAT, and VAT were each associated with higher ALM but lower muscle quality, particularly in obese women. Higher SAT (P=0.05) and VAT (P=0.04) were associated with higher quadriceps strength in women with BMI<30 kg/m^2 but not in obese women.

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Research involving Human Participants and Informed Consent: This study was performed in accordance with the Declaration of Helsinki. All study participants gave informed consent for the parent Framingham Heart Study, which was approved by the IRB at Boston University. The current study utilized previously collected data and the protocol was approved by the Institutional Review Board (or Ethics Committee) of Advarra (Protocol #Pro00044485).

Availability of data and materials: Data described in the manuscript, code book, and analytic code will be made available upon request pending application to and approval by the Framingham Heart Study.

Conclusions: Higher abdominal fat may be associated with greater lean mass but poorer muscle quality, particularly in obese women. This suggests that adipose tissue may have endocrine influences on muscle, which should be confirmed in longitudinal studies.

Keywords

muscle; epidemiology; sarcopenia; obesity

Introduction

Globally, the number of older adults is projected to grow to nearly 1.5 billion by 2050 (1). As the aging demographic shifts, conditions that affect older adults are of growing public health concerns. Fifteen percent of Americans aged 60 years and older, and half of Americans aged 80 years and older have sarcopenia, (2, 3) a disease characterized by muscle weakness, low muscle quantity/quality, and impaired physical function. (4) Sarcopenia contributes to reduced mobility, disability, institutionalization, and mortality (5, 6) with substantial associated healthcare costs. (7) Despite the gravity of this condition, the exact etiology of sarcopenia is not fully understood.

Aging is associated with an accumulation of body fat that parallels loss of muscle mass and strength. Both aging and obesity are characterized by low levels of inflammation, an independent risk factor for loss of muscle mass, strength, (8-11) and physical function (12). Adipose tissue secretes adipocytokines, a family of hormones and cytokines that are catabolic to muscle. (11, 13-15) Higher fat mass is also associated with lower circulating adiponectin, which may have positive effects on muscle through its anti-inflammatory properties (16, 17) or its influence on muscle glucose metabolism. (18-20) These metabolic changes are determined not only by fat mass, but also by fat distribution. Indeed, abdominal adiposity is more strongly predictive of cardio-metabolic disease, morbidity, and mortality versus whole body estimates of fat mass.(21) Even when considering the impact of abdominal fat, the visceral and subcutaneous compartments may have separate, independent systemic endocrine effects.(22, 23) Visceral adipose tissue (VAT) is particularly metabolically active and releases adipocytokines such as adiponectin, leptin, resistin, and interleukin-6 (IL-6).(24) There is, however, strong evidence that subcutaneous adipose tissue (SAT) also secretes adipocytokines directly into circulation.(25) While obesity and abdominal obesity are considered to be risk factors for disability (26-29) and poorer physical function (30), whether abdominal adiposity is an independent determinant of decline in muscle health is not known, nor is the physiologic mechanism for this hypothesized link. Yet few prior clinical studies have examined the interrelations of fat, adipocytokines, and muscle health. A longitudinal study of older adults reported that greater DXA-derived total fat mass was associated with lower muscle quality, and accelerated loss of lean mass over 7 years, which was not explained by higher levels of adipocytokines (31). These previous studies tended to include very old healthy adults, and used DXA-estimates of fat depots instead of measures from computed tomography (CT), which can accurately distinguish between SAT and VAT (24, 32), particularly in obese women.(33)

Given the gaps in literature, the primary objective of this study was to determine if abdominal fat is associated with poor muscle health. The secondary objective was to determine whether inflammatory markers may lie on the mechanistic pathway for the impact of abdominal fat on muscle. We hypothesized that higher waist circumference, VAT, and SAT would each be associated with lower lean mass, muscle strength, and upper extremity muscle quality, and that these associations would be at least partly mediated by markers of inflammation [IL-6, monocyte chemoattractant protein-1 (MCP-1), resistin, and adiponectin].

Methods

Study Design and Sample

This cross-sectional study included 962 members of the Framingham Study Offspring Cohort, which was composed of the adult children, and their spouses, of those enrolled in the population-based Framingham Study Original Cohort. The Offspring Cohort began in 1971 to investigate familial risk factors for cardiovascular disease within the cohort. The study enrolled 5,124 men and women (age range 5–70 y), and they have been examined at approximately 4-8 year intervals.(34) Measurements for the present study were ascertained in 1998-2001.

Inclusion and Exclusion Criteria

Inclusion criteria for this analysis included documentation of at least one measure of abdominal adiposity (waist circumference or CT fat mass) and one lean mass or muscle strength measure taken during the examinations in 1998-2001. Of the Offspring Cohort members who survived and participated in examinations in 1998-2001, 1,394 individuals with waist circumference measures, 1,042 individuals with whole body DXA scans, 997 individuals with grip strength measures, and 1,319 individuals who participated in the Multi-Detector Computer Tomography (MDCT) study and had abdominal CT scans were considered for the current study (Figure 1). Individuals who participated in the MDCT study included men aged ≥35 years and non-pregnant, women aged ≥40 years. Due to MDCT scanner constraints, those who weighed >160kg were excluded.(35) Twenty-nine males and 40 females were excluded due to missing covariate information. The final analytic sample included 962 participants (428 males and 534 females).

Abdominal Adiposity Measures

We included three measures of abdominal adiposity: waist circumference; VAT; and SAT measured in the abdominal area. Waist circumference (inches) is considered the most reliable surrogate of visceral adiposity (36) and was measured by a trained professional applying an anthropometric tape at the level of the umbilicus, recording the reading at mid-inspiration with the participant breathing normally and rounding to the nearest 0.25 inches.(37) VAT (cm^3) and SAT (cm^3) volumes were calculated from CT scans of the abdomen as previously published.(38) Twenty-five consecutive 5 mm-thick slices using an 8-slice multidetector CT scanner (LightSpeed Ultra; General Electric, Milwaukee, WI) were obtained with participants lying in a supine position. A three-dimensional (3D) workstation tool (Aquarius 3D Workstation; TeraRecon Inc, San Mateo, CA) was used to evaluate CT slices for abdominal adipose tissue quantity and density. Trained technicians outlined the abdominal muscular wall manually, identifying a designated region of interest. Using a radiographic pixel threshold between −195 and −45 HU with center attenuation of −120 HU, SAT and VAT regions were automatically identified. Mean SAT and VAT volumes in cm^3 were recorded as was attenuation in HU.

Lean mass and muscle strength

Measures of lean mass—Appendicular lean mass (ALM, kg) was calculated from whole body DXA scans obtained from a Lunar DPX-L (Lunar Radiation Corp. Madison, WI) in the fast mode with participants in standard positioning per recommendations of the manufacturer.(39) ALM was calculated as the sum of the lean mass of the arms and the legs.

Measures of muscle strength—Grip strength (kg) was measured using an adjustable Jamar isometric hand-held dynamometer. Participants squeezed the dynamometer maximally for 3 seconds. A total of six trials were done with three trials on each hand. The maximum value, regardless of the hand from which it was taken, was used for analysis. (39)

Quadriceps strength (kg) was measured using a Nicholas hand-held isometric dynamometer (test-retest reliability >85%).(40) The right leg was preferentially assessed, but in the case that the right leg could not be measured, the left was measured in its place. A single tester was used to perform all measurements. To test, participants were to be seated with hands in lap, back against the chair, and knee at 60^{o} flexion with the foot flat on the floor. The dynamometer was positioned perpendicular to the leg along the anterior tibial surface 6 cm above the lateral malleolus. The participant was instructed to extend his/her leg maximally for 3 seconds. This procedure was repeated and the higher of the two measurements was used for analysis.

Upper extremity muscle quality—Upper extremity “muscle quality,” or strength per kg of lean mass (41) was calculated as baseline grip strength (kg) divided by lean mass (kg) of the “arms region”, (entirety of upper extremities).

Circulating markers of inflammation—We assessed 4 adipocytokines as potential mediators: IL-6, MCP-1, resistin, and adiponectin. Serum IL-6, MCP-1, resistin (R&D Systems), and adiponectin (Quantikine) were measured in duplicate by ELISA from fasting blood samples collected and stored at −80°C.(42) Intra-assay coefficients of variation (% CV) for are 3.1±2.2 (IL-6), 3.8±3.3 (MCP-1), 9.0±2.0 (resistin), and 5.8±0.6 (adiponectin). (43) Standard quality control evaluations were performed and all intra-assay coefficients of variation were <10%. The details of the assays and measurements have been described in previous studies.(42, 44)

Covariables

Covariable information was collected in 1998-2001 and included sex, age, height, weight, body mass index (BMI), physical activity, smoking, and menopausal status in females. Height in inches (in) was measured with shoes removed, rounding to the nearest quarter inch using a stadiometer. Weight in pounds (lbs.) was measured with participants only wearing light clothing using a standardized balance beam scale. BMI was calculated by dividing the weight in kg by the square of height in meters (kg/m^2). Physical activity was assessed based on the Physical Activity Scale for the Elderly (PASE) score, a questionnaire used for self-reporting of physical activity over the past 7 days (13). The smoking status of the participants was assessed via questionnaire as current versus noncurrent smokers. Women's menopausal status was categorized into two groups: postmenopausal women (defined as women who reported no menstrual periods for at least 1 year or were currently using hormone replacement therapy) versus premenopausal women.

Statistical Analyses

Baseline measurements differed between males and females, therefore, sex-stratified analyses were performed. Additionally, due to high Pearson's correlation coefficients between BMI and abdominal adiposity measures, models were stratified by BMI <30 kg/m^2 and ≥30 kg/m^2. Abdominal adiposity measures (waist circumference, VAT, and SAT) were first converted into corresponding z-scores and then modeled as continuous variables. In primary analyses, sex-specific multivariable linear regression was used to calculate regression coefficients (β) for the differences in muscle mass, muscle strength, and muscle quality associated with a 1 SD higher WC, VAT and SAT within each strata of BMI. All models were adjusted for age, height, physical activity, current smoking, and menopause status in women only. We also calculated Pearson's correlation coefficients of BMI with each of the abdominal adiposity measures.

In secondary analyses, final sex- and BMI- stratified models were further adjusted for the inflammation markers, one marker at a time. If the added biomarker variable was significantly associated with the dependent variable in the regression model (regression coefficient P-value less than 0.05) and changed the main effect of WC, VAT or SAT by ≥10% compared to the model without the biomarker, we concluded that the association of WC, VAT or SAT with the dependent variable was explained, at least in part, by the added biomarker. (45)

A nominal 2-sided P value of 0.05 was considered statistically significant for the analyses. All analyses were conducted using SAS software version 9.4 (SAS Institute Inc., Cary NC).

Results

Baseline characteristics are shown in Table 1. Mean age of the participants was 60 years. Men weighed more, had higher BMI, physical activity, waist circumference and VAT compared with women. As expected men also had higher lean muscle mass and muscle strength measures while women had higher SAT values compared with men. Muscle quality values were similar in men versus women.

In the initial sex-stratified analysis, each standard deviation higher measure of adiposity (WC, SAT or VAT) was associated with higher ALM and lower muscle quality (kg grip strength per kg of arms lean mass) in men and in women (each $P<0.0001$, Table 2). No significant associations were observed for muscle strength.

BMI was highly correlated with waist circumference (correlation coefficient (r): 0.91 in men, 0.89 in women), SAT (r: 0.74 in men, 0.81 in women), and VAT (r: 0.63 in men, 0.69 in women), with P<0.001 for all correlations. These high correlations supported stratification of men and women by BMI (<30 kg/m^2 and ≥30 kg/m^2). As shown in the BMI stratified results in Table 3, in men, regardless of their BMI category, higher WC was associated with higher lean mass but lower muscle quality. Higher SAT was associated with higher lean mass and lower muscle quality in men with BMI<30, but not in obese men (Table 3). No associations were observed between VAT and either quadriceps strength or grip strength (Table 4).

For women, as shown in Table 3, higher WC, SAT, and VAT were each associated with higher lean mass but lower muscle quality although the magnitude of associations was stronger in obese women. In women with BMI<30 kg/m^2 but not in obese women, higher WC and SAT were each associated with higher quadriceps strength [β (SE): BMI<30 kg/m^2, WC= 0.832 (0.420); P= 0.05 and SAT= 0.770 (0.381); P= 0.04). Similar associations were observed for VAT but the associations did not reach statistical significance (P=0.11, Table 4). No statistically significant associations between adipose measures and grip strength were observed.

Mediation by adipocytokines

In men with BMI<30 kg/m^2, association of higher SAT with higher ALM was partly mediated by adiponectin [β (SE) for SAT: BMI<30 kg/m^2, 0.420 (0.222); P=0.06] such that the magnitude of the association was lower compared to the fully adjusted model without adiponectin [β (SE) for SAT: BMI<30 kg/m^2, 0.602 (0.193); P=0.006]. Other biomarkers did not have a significant impact on the magnitude of association for any of the adiposity measures with any of the outcomes in men or women with BMI<30 kg/m^2 (data not shown). Inflammatory biomarkers did not have a significant impact on the magnitude of association for any of the adiposity measures with any of the outcomes in men or women with BMI≥30 kg/m^2 (data not shown).

Discussion

These results suggest that in both men and women, higher adiposity is associated with higher muscle mass as measured by appendicular lean mass but lower muscle quality captured by the amount of muscle strength per unit of lean mass. These findings persisted across the two BMI groups (BMI<30 kg/m^2 and ≥30 kg/m^2). Abdominal adiposity was not consistently associated with measures of muscle strength that did not account for the force per unit of lean mass. In men with BMI<30 kg/m^2, association of higher SAT with higher ALM was partly explained by adiponectin while no such contribution by inflammatory biomarkers was observed in women.

In 2,623 men and women aged 70-79 from Health ABC study, a cross-sectional analysis reported that those at the high and low extremes of percentage of body fat (from DXA) had lower levels of leg muscle quality (calculated as the ratio of strength to muscle mass for both upper and lower extremities) than those in the midrange (41). This effect was small, but of similar magnitude to that of age itself in its effect on muscle quality, in that the negative effect of a kg fat was similar to that of a year of age. While the current study did not examine total body fat, results from abdominal body fat showed similar inverse association such that in men, one unit higher z-score for SAT was associated with 1kg (SD: 0.12) higher ALM and with 0.51 kg (0.07) lower muscle strength per kg of arms lean mass (muscle quality). Similarly, in women, one unit higher z-score for SAT was associated with 1kg (SD: 0.08) higher ALM and with 0.94 kg (0.09) lower muscle strength per kg of lean mass. The association in women was largely driven by obese women. Findings from the current study are also consistent with the results from a longitudinal study from Health ABC, which reported that every *SD* greater DXA-derived fat mass was related to 1.3 kg more leg lean mass at baseline in men and 1.5 kg in women ($p < .01$). However, over 7 years of follow-up, greater fat mass was associated with associated with lower muscle quality, and it predicted accelerated loss of lean mass over 7 years, which was not explained by higher levels of adipocytokines (31).

A few prior studies suggest that abdominal obesity measured by waist circumference is associated with increased functional limitations and disability (27, 29). A meta-analysis of 50 prospective, longitudinal studies of older persons aged 65± years reported that BMI of 30 kg/m^2 and above was associated with 60% higher odds of functional decline [pooled OR (95%CI) = 1.60 (1.43-1.80). However, results from the current study showed no significant association of any of the adiposity measures with grip strength in any of the BMI groups. Associations of adiposity measures with quadriceps strength were inconsistent such that higher WC, SAT, and VAT were associated with higher quadriceps strength only in normal and overweight women but not in obese women or in men. Associations for VAT did not reach statistical significance.

Age-related declines in muscle mass and muscle quality as reported in previous studies (41, 46) could be due to advanced age of these participants compared to the participants of the current study. Additionally, discrepant findings could be due to decreased proportion of type II fibers, increased connective tissue, fatty infiltration, and altered muscle metabolism. In obesity, upregulation of MCP-1 is associated with macrophage accumulation and activation in adipose tissues, and insulin resistance. (47) Significantly raised MCP-1 levels and IL-6 levels in obese and sarcopenic obese older adults support the theory of chronic inflammation due to excess adiposity (15, 47). Resistin is released by adipocytes during adipocyte differentiation and has been known to mediate insulinotropic action and fat accumulation potentially at the expense of muscle strength. (11, 48) Lower adiponectin levels are found in inactive obese individuals and shows an inverse relationship with muscle strength, particularly in older adults. (11) In spite of the strong rationale for mediation of the association of adiposity measures and muscle measures by inflammatory markers, no such mediation was observed for IL-6, MCP-1, and resistin in the current study. However, in men with BMI<30 kg/m^2, the association of higher SAT with higher ALM was partly mediated by adiponectin, while no such mediation by inflammatory biomarkers was observed in obese men or in women. Given the weak correlation between adiponectin and SAT in men ($r = -0.04$, $P = 0.41$), this unexpected association in men with BMI in the normal or overweight range could be due to random chance given the multiple tests that were performed for four inflammation markers.

This present study is one of the first to examine association of specific abdominal fat depots with muscle characteristics. Use of an established population-based cohort with large numbers of men and women across a wide age range is a strength of this study. The Framingham Study Offspring cohort is well-characterized, enabling us to examine several measures of muscle and physical function while accounting for potential confounding variables. This study has some limitations. The cross-sectional design precludes causal inferences linking abdominal fat depots with lean mass and muscle quality and identifying adipocytokines as a physiologic mechanism. CT scans were collected as a part of the MDCT study, which could not include extremely obese individuals due to weight limits for the table attached to the CT scanner. The results of this study are predominantly generalizable to males and females of European ancestry. Given the observational nature of this study, the results may be affected by residual confounding.

Conclusions

This study suggests that higher abdominal adiposity is associated with higher lean mass but lower muscle quality in men and women. These associations persisted across the two BMI groups. The magnitude of associations was stronger in obese women. These results suggest that although larger amounts of body fat may confer greater lean mass, the strength of the muscle per unit of lean mass is adversely associated with fat depots regardless of location. While these findings raise the possibility that adipose tissue can have endocrine influences on muscle function, future studies should determine the mechanisms that may link adipose tissue and muscle quality. Longitudinal studies are needed to confirm findings from this cross-sectional study.

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Competing interests:

Dr. Sahni reports institutional grants from Dairy Management Inc., Solarea Bio Inc., has reviewed grants for the American Egg Board's Egg Nutrition Center and National Dairy Council, and she serves on a scientific advisory board for the Institute for the Advancement of Foods and Nutrition Sciences (IAFNS, unpaid position ended July 2022). Dr. Kiel has received grant funding to his institution from Amgen, Solarea Bio Inc., and Radius Health. He serves on the scientific advisory boards of Pfizer and Solarea Bio Inc. Dr. Hannan has received institutional grant funding from Amgen. Dr. Raghupathy and Dr. McLean have no relevant financial or non-financial interests to disclose related to this current work.

Abbreviations

ALM	Appendicular lean mass
DXA	Dual energy x-ray absorptiometry

WC	Waist circumference
VAT	Visceral adipose tissue
SAT	Subcutaneous adipose tissue
BMI	Body Mass Index
IL-6	Interleukin-6
CT	Computed tomography
MCP-1	Monocyte chemoattractant protein-1
MDCT	Multi-Detector Computer Tomography
3D	Three-dimensional
PASE	Physical Activity Scale for the Elderly
r	Correlation coefficient

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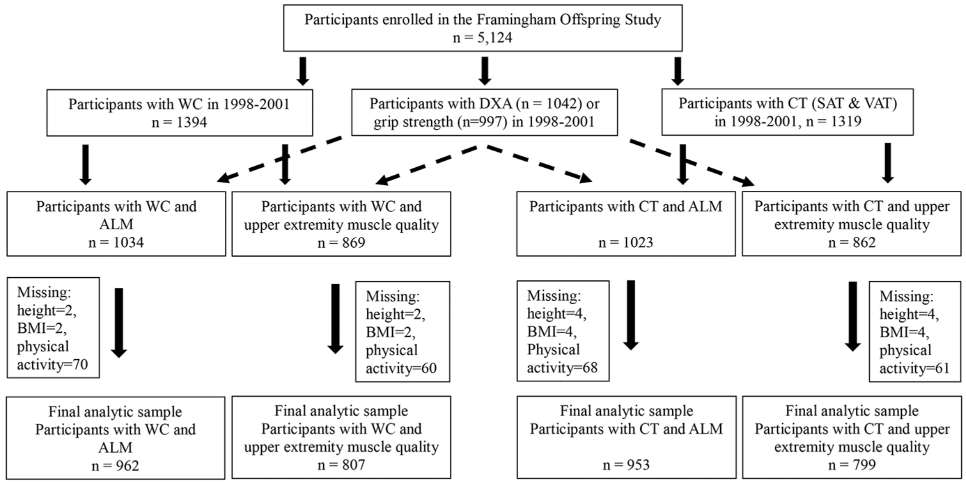

Fig 1. Flow chart showing total number of participants enrolled in the Framingham Offspring Study and the final number of participants included in the analyses

Notes. WC= Waist circumference, DXA= dual energy x-ray absorptiometry, CT= computed tomography, SAT= subcutaneous adipose tissue, VAT= visceral adipose tissue, ALM= appendicular lean mass, BMI= body mass index.

Table 1.

Baseline characteristics (mean ± standard deviation) of 549 males and 624 females from the Framingham Offspring Cohort in 1998-2001.

Sample characteristics	Male	Female
Age (years)	60 ± 9	60 ± 9
BMI (kg/m^2)	28.9 ± 4.6	27.7 ± 5.8
Height (m)	1.75 ± 0.07	1.61 ± 0.06
Weight (kg)	88 ± 15	72 ± 16
Physical activity index	38.4 ± 6.5	37.3 ± 5.5
Current smokers, n (%)	56 (10.3)	58 (9.3)
Post-menopausal women, n (%)	-	561 (89.9)
Waist Circumference (inches)	41 ± 4	38 ± 6
SAT (cm^3)	2698 ± 1108	3298 ± 1459
VAT (cm^3)	2677 ± 1119	1624 ± 856
Appendicular Lean Mass (kg)	24.7 ± 3.2	16 ± 2.3
Upper extremity muscle quality[a]	6.3 ± 1.4	6.3 ± 2
Quadriceps strength (kg)	23.2 ± 6.5	18.9 ± 5.2
Grip strength (kg)	44.2 ± 9.8	26 ± 7.7

Notes. BMI= Body Mass Index, SAT= Subcutaneous adipose tissue, VAT= Visceral adipose tissue.

[a]Upper extremity muscle quality calculated as kg of grip strength per kg of arms lean mass

Table 2.

Adjusted sex-specific associations of adiposity measures (z-scores) with appendicular lean mass (kg), upper extremity muscle quality (kg of grip strength per kg of arms lean mass), and grip strength (kg) in the Framingham Offspring Cohort in 1998-2001.

	Appendicular lean mass (kg)				**Upper extremity muscle Quality**			
	N	**β[a]**	**SE**	**P value**	**N**	**β[a]**	**SE**	**P value**
Males								
WC Z score	428	1.666	0.117	**<0.0001**	352	−0.638	0.070	**<0.0001**
SAT Z score	425	1.144	0.124	**<0.0001**	349	−0.518	0.071	**<0.0001**
VAT Z score	425	0.950	0.124	**<0.0001**	349	−0.346	0.072	**<0.0001**
Females								
WC Z score	534	1.312	0.074	**<0.0001**	455	−0.973	0.090	**<0.0001**
SAT Z score	528	1.046	0.079	**<0.0001**	450	−0.947	0.088	**<0.0001**
VAT Z score	528	0.911	0.081	**<0.0001**	450	−0.751	0.089	**<0.0001**
	Quadriceps Strength (Kg)				**Grip Strength (Kg)**			
Males								
WC Z score	438	0.386	0.303	0.20	424	0.005	0.407	0.99
SAT Z score	434	0.428	0.309	0.17	420	−0.495	0.409	0.22
VAT Z score	434	0.162	0.311	0.60	420	0.420	0.421	0.32
Females								
WC Z score	533	0.158	0.229	0.49	485	0.443	0.327	0.175
SAT Z score	527	0.213	0.224	0.34	480	0.160	0.331	0.628
VAT Z score	527	0.206	0.225	0.36	480	0.301	0.322	0.350

Notes. WC= Waist Circumference, SA= Subcutaneous adipose tissue, VAT= Visceral adipose tissue. Statistically significant results are $p \leq 0.05$ and are presented in bold.

[a]Beta coefficient adjusted for age, height, physical activity index (PAI), current smoking and menopausal status (in women),

Table 3.

Adjusted sex-specific associations of adiposity measures (z-scores) with appendicular lean mass (kg) and upper extremity muscle quality (kg of grip strength per kg of arms lean mass) stratified by BMI in the Framingham Offspring Cohort in 1998-2001.

	Appendicular lean mass (kg)				Upper extremity muscle quality			
BMI<30 kg/m^2	**N**	**β[a]**	**SE**	**P value**	**N**	**β[a]**	**SE**	**P value**
Males								
WC Z score	305	1.148	0.205	**<0.0001**	255	−0.658	0.123	**<0.0001**
SAT Z score	303	0.602	0.193	**0.002**	253	−0.450	0.118	**0.0002**
VAT Z score	303	0.291	0.165	0.08	253	−0.119	0.102	0.24
Females								
WC Z score	394	0.659	0.121	**<0.0001**	342	−0.681	0.160	**<0.0001**
SAT Z score	388	0.387	0.114	**0.0008**	336	−0.718	0.144	**<0.0001**
VAT Z score	388	0.370	0.110	**0.0009**	336	−0.441	0.143	**0.002**
BMI≥30 kg/m^2								
Males								
WC Z score	123	1.556	0.334	**<0.0001**	97	−0.422	0.185	**0.02**
SAT Z score	122	0.099	0.268	0.71	96	−0.173	0.144	0.23
VAT Z score	122	0.260	0.253	0.30	96	−0.103	0.146	0.48
Females								
WC Z score	140	1.424	0.202	**<0.0001**	113	−0.999	0.209	**<0.0001**
SAT Z score	140	0.680	0.183	**0.0003**	114	−0.810	0.179	**<0.0001**
VAT Z score	140	0.404	0.157	**0.01**	114	−0.509	0.143	**0.0006**

Notes. BMI= Body Mass Index, WC= Waist Circumference, SA= Subcutaneous adipose tissue, VAT= Visceral adipose tissue. Statistically significant results are $p \leq 0.05$ and are presented in bold.

[a]Models for WC, SAT, and VAT were analyzed separately where each model was adjusted for age, height, physical activity index (PAI), current smoking and menopausal status (in women)

Table 4.

Adjusted sex-specific association of adiposity measures (z-scores) with measures of muscle strength stratified by BMI in the Framingham Offspring Cohort in 1998-2001.

	Quadriceps strength (kg)				Grip strength (kg)			
BMI<30 kg/m²	**N**	**β[a]**	**SE**	**P value**	**N**	**β[a]**	**SE**	**P value**
Males								
WC Z score	305	−0.093	0.584	0.87	299	−0.212	0.778	0.79
SAT Z score	303	−0.485	0.536	0.37	297	−1.141	0.720	0.11
VAT Z score	303	−0.171	0.446	0.70	297	0.586	0.596	0.32
Females								
WC Z score	391	0.831	0.420	**0.04**	356	0.500	0.574	0.38
SAT Z score	385	0.770	0.380	**0.04**	350	−0.109	0.527	0.83
VAT Z score	385	0.574	0.365	0.11	350	0.619	0.509	0.22
BMI≥30 kg/m²								
Males								
WC Z score	133	−0.026	0.743	0.97	125	−1.238	1.000	0.21
SAT Z score	131	0.641	0.662	0.33	123	−1.560	0.841	0.07
VAT Z score	131	−0.187	0.672	0.78	123	−0.276	0.955	0.77
Females								
WC Z score	142	−0.879	0.550	0.11	129	−0.800	0.902	0.38
SAT Z score	142	−0.560	0.491	0.26	130	−1.390	0.830	0.10
VAT Z score	142	−0.456	0.415	0.27	130	−0.752	0.645	0.24

Notes. BMI= Body Mass Index, WC= Waist Circumference, SA= Subcutaneous adipose tissue, VAT= Visceral adipose tissue. Statistically significant results are $p \leq 0.05$ and are presented in bold.

[a]Models for WC, SAT, and VAT were analyzed separately where each model was adjusted for age, height, physical activity index (PAI), current smoking and menopausal status (in women alone)