JAMDA xxx (2020) 1–9

JAMDA

journal homepage: www.jamda.com

Original Study

Muscle Density, but Not Size, Correlates Well With Muscle Strength and Physical Performance

Ling Wang MD, PhD[a,†], Lu Yin PhD[b,†], Yue Zhao BS[a], Yongbin Su MD[a], Wei Sun BS[c], Shuo Chen BS[c], Yandong Liu MD[a], Minghui Yang MD[d], Aihong Yu MD, PhD[a], Giuseppe Guglielmi MD[e], Glen M. Blake PhD[f], Xiaoguang Cheng MD, PhD[a,*], Xinbao Wu MD[d], Annegreet G. Veldhuis-Vlug MD, PhD[g,h], Klaus Engelke PhD[i]

[a] *Department of Radiology, Beijing Jishuitan Hospital, Beijing, China*
[b] *Medical Research and Biometrics Center, National Center for Cardiovascular Disease, Beijing, China*
[c] *Xinjiekou Community Health Service Center, Beijing, China*
[d] *Department of Traumatic Orthopedics, Beijing Jishuitan Hospital, Beijing, China*
[e] *Department of Radiology, University of Foggia, Foggia, Italy*
[f] *School of Biomedical Engineering and Imaging Sciences, King's College London, St Thomas' Hospital, London, United Kingdom*
[g] *Department of Internal Medicine, Division of Endocrinology, Center for Bone Quality, Leiden University Medical Center, Leiden, the Netherlands*
[h] *Jan van Goyen Medical Center, Department of Internal Medicine, Amsterdam, the Netherlands*
[i] *Department of Medicine 3, FAU University Erlangen-Nürnberg and Universitätsklinikum Erlangen, Erlangen, Germany*

Keywords:
Muscle density
muscle size
grip strength
Timed Up and Go test
sarcopenia
computed tomography

A B S T R A C T

Objectives: There is increasing evidence that muscle volume and mass are poor predictors of muscle strength and physical performance. Other assessments of muscle quality such as skeletal muscle density measured by computed tomography (CT) may be more important. The aim of this study was to explore associations of muscle size and density with handgrip strength (HGS) and the Timed Up and Go test (TUG). We also hypothesized that the strength of these associations would depend on the specific muscle of muscle group, namely trunk, hip, and mid-thigh muscles.
Design: Cross-sectional study.
Setting and Participants: University hospital; 316 volunteers aged 59 to 85 years.
Methods: HGS, TUG, and quantitative CT imaging of the lumber, hip, and mid-thigh were performed in volunteers. From the CT images, cross-sectional area and attenuation were determined for the gluteus muscle, trunk muscle at vertebrae L2 level, and mid-thigh muscle.
Results: In men and women, associations of muscle area with TUG were insignificant after adjustment for age, height, and weight. Associations with HGS were only significant in men for the gluteus maximus and the mid-thigh but slopes were rather low ($\beta < 0.20$). Associations between muscle density and TUG/HGS were more pronounced, in particular for HGS. After adjustment, associations with TUG were significant in women for the gluteus maximus and trunk muscle even (β −0.06, P .001 and β −0.07, P .031, respectively).
Conclusions and Implications: Muscle density is more strongly associated with muscle strength than muscle size andin women muscle density was also more strongly associated than muscle size with physical performance. Therefore, muscle density may represent a more clinically meaningful surrogate of muscle performance than muscle size. Muscle density measurements of trunk and gluteus muscles can be easily obtained from routine CT scan and, therefore, may become an important measurement to diagnose and screen for sarcopenia.

This work was supported in part by the National Natural Science Foundation of China (Grant no. 81901718; 81971617; 81771831), the Beijing Natural Science Foundation-Haidian Primitive Innovation Joint Fund (grant no. L172019), and the Beijing Municipal Administration of Hospitals Clinical Medicine Development of Special Funding Support (code: XMLX201843).

Klaus Engelke is a part time employee of BioClinica, Inc. The other authors declare no conflict of interest.

* Address correspondence to Xiaoguang Cheng, MD, PhD, Department of Radiology, Beijing Jishuitan Hospital, Beijing 100035, China.
E-mail address: xiao65@263.net (X. Cheng).
† Ling Wang and Lu Yin contribute equally and are co-first authors.

https://doi.org/10.1016/j.jamda.2020.06.052
1525-8610/

Loss of skeletal muscle mass is 1 criterion of sarcopenia.[1] However, the correlation of muscle mass with muscle strength and more generically with muscle function is low. Substantial decreases in skeletal muscle function with ageing can occur with only minimal loss of skeletal muscle mass.[2,3] This discrepancy may be partially related to the presence of fatty infiltration, which is 1 aspect of muscle quality. The term muscle quality, like bone quality, is a loosely defined concept that broadly includes aspects of anatomic structure, biochemical properties, and neuromuscular and metabolic performance. The assessment of these components of muscle quality may be more important than the quantification of muscle mass. One aspect of muscle quality, namely skeletal muscle density measured by computed tomography (CT) as the mean attenuation in Hounsfield Units (HU), has been widely used in research studies.[4,5]

Typical anatomic locations for skeletal muscle measurements using CT are the thigh, hip, and trunk. Muscle size (cross-sectional area, CSA) and density (mean HU) of the abdominal and mid-thigh muscles are well-established parameters used in studies of physical function, frailty, or cancer.[4,6–10] Data from healthy adults showed that thigh muscle area and attenuation were weakly associated with muscle strength and physical performance, with R values varying about from 0.2 to 0.4.[8,11,12] Interestingly, studies using quantitative imaging of hip and sacrum muscles are sparse despite a major role of these muscles in gait variability and maintenance of body stability. Also, the respective contributions of these muscles to strength and physical performance have not been previously studied.

The main aim of this study was to explore associations of muscle size and density with muscle strength and physical performance as assessed by the handgrip strength (HGS) and the Timed Up and Go test (TUG). For this purpose, we used data from the China Action on Spine and Hip Status study on healthy men and women aged 59 to 85 years. We also aimed to explore the associations of muscle size and density with the physical performance of different muscle levels. We hypothesized that older adults with lower muscle density, but not smaller muscle size, exhibited lower muscle strength and poorer physical performance, and that compared with the mid-thigh and trunk muscle, hip muscle correlated better with physical performance.

Methods

Study Design

China Action on Spine and Hip Status study determines the prevalence of osteoporotic fracture, osteoporosis, and osteoarthritis in an older Chinese population using quantitative CT and/or dual energy X-ray absorptiometry (DXA).[13] The present subanalysis of healthy individuals used quantitative CT scans of the lumbar spine, hip, and mid-thigh. In this cross-sectional analysis, we investigated and compared CT-based muscle measurements with HGS used as surrogate for muscle strength and TUG used as surrogate for physical performance. We also determined the associations of CT muscle size/density of different muscle levels (trunk, gluteal, and mid-thigh) with HGS and TUG.

Participants

Three hundred sixteen community-dwelling individuals of at least 50 years and in good health were recruited between March 2017 and June 2017 from the neighborhood of our hospital. Exclusion criteria were inability to sit and stand independently, inability to walk with or without an assistive device (only relevant for TUG), or pain that prevented testing. Further exclusion criteria were stroke, neurologic disorders, metabolic diseases, rheumatic diseases, heart failure, severe chronic obstructive pulmonary disease, coagulation disorders, and other diseases that limited function. The study was approved by the ethics committee of our hospital (approval number No. 201512-02). Informed consent was obtained from each participant.

CT Acquisition

Spiral CT imaging of the hip was performed for all study participants with a Toshiba Aquilion CT scanner (Toshiba Medical Systems Division, Tokyo, Japan). Scans were acquired in supine position from the top of the acetabulum to 3 cm below the lesser trochanter and included both legs. In addition, CT scans of the lumbar spine including vertebrae L1–L5 and of a 1-cm thick section of the center of the left thigh were taken. The position of this section was determined from a scout view as the center of the long axis of the femur. Scan parameters for all CT scans were 120 kVp, 125 mAs, 50 cm field of view, 512×512matrix, 1-mm reconstructed slice thickness, and a standard reconstruction kernel with filtered back projection.

Muscle Density Assessments

CSA and density of the following muscle or muscle groups were measured on 1 slice each. In the hip, the gluteus maximus at the level of the greater trochanter and the gluteus medius and minimus muscle at the level of S3 were analyzed. In the trunk the paraspinal muscles (erector spinae and transversospinalis), the posterior abdominal muscles (psoas major and quadratus lumborum), and the anterior abdominal muscles (rectus abdominis, external and internal oblique) were analyzed at the level of L2 (Figure 1). Finally, in the thigh, the ensemble of all muscles was analyzed.

The hip CT scan range of 97 participants did not cover the S3 level, so we only measured gluteus medius and minimus muscle density and area at S4 or S5 levels. Supplementary Table 1 shows there was no significant difference in muscle density between the S3 and non-S3 levels; the numerical difference of 0.8 HU was very small and could be considered negligible. Difference in muscle area between the S3 and non-S3 levels was either not significant, however, the absolute difference of about 4.1 cm^2 accounted to a 10% bias compared with the mean area value at the S3 level. For this reason, we did not include gluteus medius and minimus muscle CSA in the analysis.

OsiriX software (Lite version 10.0.2; Pixmeo, Geneva, Switzerland) was used for analysis. Muscle segmentation was performed manually using the “pencil” tool to outline muscle contours. Then the Grow-Region tool of the 2-demensional/3-dimensional segmentation module was used to semiautomatically select skeletal muscle regions within the preset HU intensity thresholds (−30 to 150 HU). Within the resulting regions of interest, a threshold of −29 HU was applied to distinguish muscle tissue from fat. Finally, the muscle CSA and density values of the regions of interest were displayed on the screen. All muscle measurements were performed by the same investigator who had received training by an expert radiologist in CT muscle imaging prior to the analysis. For training, a sample of about 20 images had been analyzed together with the expert prior to the beginning of the measurement study. Excellent intraobserver (intraclass correlation coefficients 0.932–0.998, $P < .001$) and interobserver (intraclass correlation coefficients 0.913–0.961, $P < .001$) agreements of the muscle measures were found.

Muscle Strength Assessments

HGS of the dominant hand was measured using a Jamar dynamometer (Jamar, Los Angeles, CA). Three attempts with a 1-minute

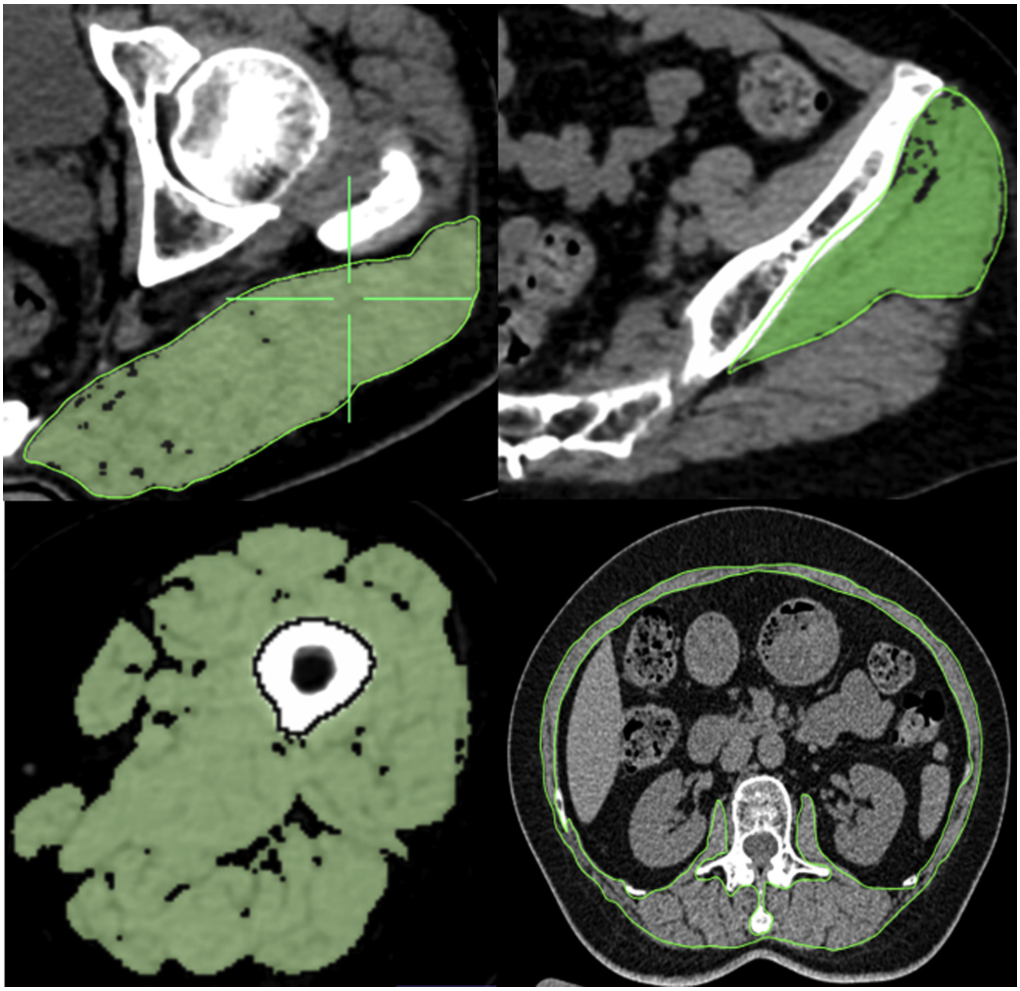

Fig. 1. Measurement of cross–sectional area and mean CT values of the left gluteus maximus at the level of the greater trochanter of the femur; Measurement of the left gluteus medius and minimus muscle at the 3rd sacral (S3) level; Measurement of the left mid–thigh muscle group; Measurement of the trunk muscle at mid–L2 level.

interval between them were recorded in kilograms, and the maximum value was used for further analysis. Details of measuring grip strength were previously reported.[14]

Physical Performance

The TUG test was performed by measuring the time needed by an individual to rise from an armchair, walk 3 meters on a line drawn on the floor, turn, and walk back to the chair to a seated position. Physical support is not permitted. Details of TUG test were previously described.[14] The rater who supervised the TUG tests had been trained in detail on how to instruct participants.

Bone Mineral Density

Areal bone mineral density (aBMD, g/cm^2) of the femoral neck and total hip was calculated from the hip CT scans using the CT X-ray absorptiometry technique (CTXA v 4.2.3, Mindways Inc., Austin, TX). The good precision of CTXA aBMD measurements was reported previously with root-mean-square error from 0.012 to 0.024 g/cm^2.[15] The Medical Image Analysis Framework option Femur (MIAF Femur v 7.1.0MRH, Klaus Engelke, Erlangen) was used to measure 3-dimensional femoral neck cortical thickness.[13]

Data Collection

Demographic and anthropometric variables included age, sex, body mass index, hip circumference, and waist circumference. Health-related data included blood pressure, fracture history, and the EuroQol 5-dimension score (EQ-5D). In this study, EQ-5D with 3 levels of severity (EQ-5D-3L) was used. It included 5 dimensions (mobility, self-care, usual activities, pain or discomfort, anxiety or depression) divided into 3 levels of severity (no problems, some problems, severe problems) describing 243 unique health profiles.[16] Other health-related data were retrieved from the patient's medical file or from the healthy participants' medical records.

Statistical Analyses

All statistical analyses were conducted using SAS v 9.4 (SAS Institute Inc, Cary, NC). Categorical variables were described as counts and corresponding percentages. Continuous variables were presented as mean ± standard deviation. Differences between female and male participants were analyzed using Mann-Whitney U or Kruskal-Wallis tests for continuous variables, and the χ^2 test for categorical variables. General linear models were fitted using the method of least squares to evaluate associations of TUG and HGS with muscle CSA and density, adjusted for age, height, and weight. The interaction of sex and age group was also assessed. Sex-specific quartiles of muscle CSA and density were also evaluated with EQ-5D in unadjusted and adjusted general linear models.

Results

Study Cohort Characteristics

Eight of the 316 participants were excluded from the study because of either invalid HGS or TUG measurements, or because of inability to complete the TUG test. Seven additional participants were excluded because of missing CT scans or unacceptable image quality (ie, artifacts). Of the remaining 301 participants, 107 were men and 194 women. Fourteen men and 25 women had no CT scans of the lumbar spine. Thus, for trunk muscle assessments, only 93 men and 169 women were included in the final analysis.

Characteristics of the study cohort are shown in Table 1. Women were younger than men ($P = .02$), and, as expected, had lower HGS, lower muscle CSA and density (trunk, gluteus, and thigh), lower aBMD in total hip and femoral neck regions, lower cortical thickness of the femoral neck, and lower hip and waist circumference. There were no differences in body mass index, TUG, EQ-5D, blood pressure, or fracture history.

The Levels of Muscle Parameters by Sex and Age Groups

Figure 2 shows sex- and age-specific differences of muscle area and density. In general linear models, men had significantly higher muscle size and density than women for all 3 age groups ($P < 0.05$), except for gluteus maximus muscle density ($P = .059$). In both sexes, muscle area and density did not vary with age with the following exceptions: mid-thigh muscle area decreased at high age group of men and women ($P = .027$) in post-hoc analyses using general linear models. In addition, gluteus maximus muscle density was lower in the female with the highest age group, but this trend was not observed in males ($P_{interaction} = 0.046$). No significant interaction was found for other muscle area and density results, including gluteus maximus muscle area, trunk muscle area and density at L2, mid-thigh muscle area, and density ($P_{interaction} > 0.05$).

Relation Between Muscle Parameters and TUG/HGS

Results are summarized in Table 2 for muscle area and density, and graphically shown for density in scatter plots of Figure 3. Associations between muscle area and TUG/HGS were poor. In men and women, associations with TUG were insignificant after adjustment for age, height, and weight. Associations with HGS were only significant in men for the gluteus maximus and the mid-thigh, but slope was rather low ($\beta < 0.2$).

Associations between muscle density and TUG/HGS were more pronounced, in particular for HGS. After adjustment for age, height, and weight, associations with TUG were significant in women for the gluteus maximus and trunk muscle even. Associations with HGS were significant for both sexes for all muscle groups with the exception of the mid-thigh muscle in women.

Relation Between Muscle Parameters and EQ-5D

Associations of muscle area and density with EQ-5D were not significant after adjusting for age, height, and weight. Supplementary Figure 1 shows the combined results divided into quartiles for male and female participants.

Relation Between aBMD and TUG/HGS

Supplementary Figure 2 shows that in both sexes femoral neck aBMD was positively associated with HGS but not with TUG. However, after adjustment for age, height, and weight, the associations between femoral neck aBMD and HGS were no longer significant ($P_{\text{for trend}} > 0.05$).

Discussion

To our knowledge, this is the first study to compare associations of trunk, hip, and thigh muscles size and density with muscle strength

Table 1
Characteristics of Study Participants

Characteristics (Mean ± SD)	Total (n = 301)	Men (n = 107)	Women (n = 194)	P Value*
Age (y)	68.4 ± 6.1	69.6 ± 6.6	67.7 ± 5.8	.02
Weight (kg)	66.8 ± 10.0	72.4 ± 9.4	63.7 ± 9.0	<.01
Height (cm)	162.5 ± 7.5	169.7 ± 5.1	158.5 ± 5.3	<.01
BMI (kg/cm^2)	25.2 ± 2.9	25.1 ± 2.6	25.3 ± 3.1	.42
TUG time (s)	8.2 ± 1.5	8.2 ± 1.5	8.3 ± 1.6	.64
HGS (kg)	25.6 ± 8.5	34.0 ± 7.3	21.0 ± 4.8	<.01
EQ-5D	0.6 ± 0.2	0.6 ± 0.2	0.6 ± 0.1	.33
Gluteus maximus muscle area (cm^2)	39.4 ± 7.4	43.1 ± 7.9	37.3 ± 6.3	<.01
Gluteus maximus muscle density (HU)	33.4 ± 6.6	35.8 ± 6.5	32.1 ± 6.3	<.01
Gluteus medius and minimus muscle density (HU)	42.3 ± 4.4	43.4 ± 4.2	41.8 ± 4.4	<.01
Muscle area of mid-thigh (cm^2)	103.9 ± 22.9	123.6 ± 22.2	93.1 ± 14.5	<.01
Muscle density of mid-thigh (HU)	45.1 ± 4.0	46.7 ± 3.6	44.2 ± 3.8	<.01
Trunk muscle areas at vertebral L2 (cm^2)	102.9 ± 23.6	125.9 ± 19.3	90.3 ± 14.4	<.01
Trunk muscle density at vertebral L2 (HU)	29.0 ± 4.4	30.7 ± 4.5	28.0 ± 4.1	<.01
Waist circumference (cm)	86.6 ± 8.6	89.9 ± 8.0	84.8 ± 8.4	<.01
Hip circumference (cm)	98 ± 13.5	99.3 ± 16.2	97.4 ± 11.8	.01
Systolic blood pressure (mm Hg)	126.5 ± 8.6	126.5 ± 8.9	126.5 ± 8.5	.71
Diastolic blood pressure (mm Hg)	74.1 ± 7.6	74.7 ± 5.9	73.8 ± 8.3	.37
Total hip aBMD (g/cm^2)	0.8 ± 0.2	0.9 ± 0.2	0.8 ± 0.1	<.01
Femoral neck aBMD (g/cm^2)	0.7 ± 0.1	0.7 ± 0.1	0.7 ± 0.1	<.01
Cortical thickness of femoral neck (mm)	1.8 ± 0.3	1.9 ± 0.3	1.8 ± 0.3	<.01
Previous fracture, % (n)	16.9 (51)	19.6 (38)	12.2 (13)	.10

BMI, body mass index; SD, standard deviation.
*P value was obtained from 2-sample Wilcoxon tests for continuous variables and χ^2 tests for categorical variables.

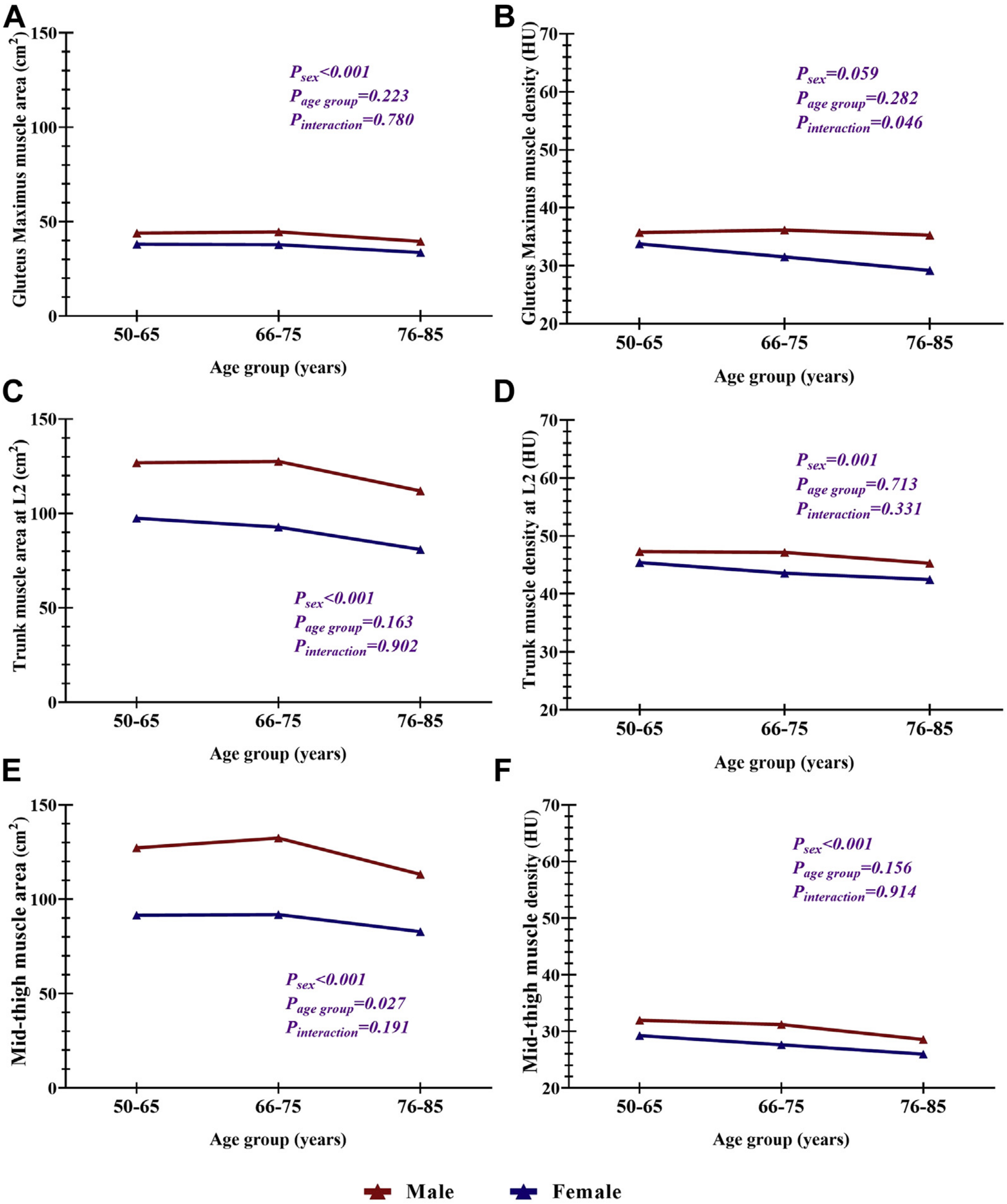

Fig. 2. Gluteal, L2–trunk, and mid–thigh muscle area and density by age and sex.

and physical performance parameters. As a main result, our study demonstrates that muscle density correlates better than muscle size with handgrip strength in both sexes and also in women with TUG. Skeletal muscle density as measured by CT reflects the amount of intramuscular fat content,[12] which is ignored when solely quantifying muscle area, although this likely affects muscle function. So far, in the vast majority of muscle imaging studies, muscle area but not density was obtained as the primary outcome.[4,17] Our study, however, indicates that indeed muscle density correlates better with functional outcomes and, therefore, may be more clinically relevant to measure than muscle size. This is in agreement with earlier studies[18–22] that emphasized the importance of intramuscular fat content and distribution for muscle function.

This important finding may be highly relevant for the definition of sarcopenia. Initial definitions relied on appendicular muscle mass as determined by DXA or by bioimpedance analysis, but recent international consensus statements such as those from the Asian Working Group for Sarcopenia (AWGS) in 2019 and from the European Working Group on Sarcopenia in Older People in 2018[1,23] put higher emphasis on physical function than on muscle mass. Also, the role of CT or magnetic resonance imaging (MRI) to measure muscle size as a diagnostic criterion of sarcopenia has not been well specified. Muscle mass and size are only weakly correlated with muscle function. The use of muscle density by CT and fat fraction by MRI better characterize muscle quality and may assign a more prominent role to CT and MR in the diagnosis of sarcopenia in treatment planning and in monitoring response to treatment.[1] The findings in our study provide evidence that muscle density assessed by CT imaging may be a sensitive screening tool for sarcopenia using opportunistic analysis of existing clinical CT scans.

We also explored the relation of muscle size and density with muscle strength and physical performance at different levels, namely

Table 2
Sex-specific Correlation Coefficient and 95% CI Between Muscle Area or Density and HGS or TUG

Muscle Area and Density	Men				Women			
	TUG (s)		Handgrip (kg)		TUG (s)		Handgrip (kg)	
	Unadjusted	Adjusted*	Unadjusted	Adjusted*	Unadjusted	Adjusted*	Unadjusted	Adjusted*
Gluteus maximus muscle area (cm^2)								
β (95% CI)	0.011 (−0.026, 0.048)	0.016 (−0.027, 0.059)	0.320 (0.152, 0.488)	**0.174 (–0.015, 0.363)**	–0.043 (−0.078, −0.009)	–0.036 (−0.076, 0.004)	0.174 (0.068, 0.280)	0.054 (−0.070, 0.179)
P value	.549	.456	<.001	**.037**	.015	.080	.001	.390
Gluteus maximus muscle density (HU)								
β (95% CI)	–0.042 (−0.086, 0.002)	–0.036 (−0.082, 0.010)	0.19 (−0.023, 0.403)	**0.293 (0.094, 0.493)**	–0.075 (−0.109, −0.042)	**–0.060 (–0.095, –0.025)**	0.125 (0.017, 0.232)	**0.122 (0.013, 0.230)**
P value	.061	.122	.080	**.004**	<.001	**.001**	.023	**.029**
Muscle area of mid-thigh (cm^2)								
β (95% CI)	0.004 (−0.009, 0.018)	0.007 (−0.007, 0.022)	0.144 (0.086, 0.201)	**0.100 (0.036, 0.163)**	–0.020 (−0.035, −0.005)	–0.009 (−0.028, 0.001)	0.105 (0.060, 0.149)	0.050 (−0.007, 0.108)
P value	.503	.323	<.001	**.003**	.008	.338	<.001	.085
Muscle density of mid–thigh (HU)								
β (95% CI)	–0.085 (−0.164, −0.006)	–0.063 (−0.147, 0.022)	0.451 (0.072, 0.831)	**0.470 (0.102, 0.839)**	–0.086 (−0.143, −0.030)	–0.045 (−0.102, 0.012)	0.176 (0.000, 0.352)	0.095 (−0.081, 0.272)
P value	.034	.145	.020	**.013**	.003	.124	.050	.288
Trunk muscle areas at vertebral L2 (cm^2)								
β (95% CI)	0.008 (−0.008, 0.024)	0.016 (−0.006, 0.039)	0.141 (0.069, 0.213)	0.063 (−0.036, 0.163)	–0.004 (−0.021, 0.013)	0.009 (−0.010, 0.029)	0.062 (0.010, 0.115)	–0.007 (−0.069, 0.055)
P value	.344	.150	<.001	.210	.622	.349	.020	.826
Trunk muscle density at vertebral L2 (HU)								
β (95% CI)	–0.065 (−0.133, 0.004)	–0.038 (−0.114, 0.037)	0.522 (0.205, 0.839)	**0.608 (0.294, 0.922)**	–0.094 (−0.151, −0.037)	**–0.068 (–0.130, –0.006)**	0.237 (0.055, 0.419)	**0.260 (0.069, 0.451)**
P value	.063	.316	.002	**<.001**	.001	**.031**	.011	**.008**
Gluteus medius and minimus muscle density (HU)								
β (95% CI)	–0.016 (−0.086, 0.054)	0.015 (−0.059, 0.090)	0.198 (−0.144, 0.540)	0.141 (−0.198, 0.480)	–0.063 (−0.113, −0.012)	–0.017 (−0.070, 0.035)	0.104 (−0.054, 0.262)	0.018 (−0.144, 0.181)
P value	.644	.680	.253	.411	.015	.514	.196	.827

The significant β and *P* values for the adjusted results are shown in bold. CI, confidence interval.
*Adjusted for age, height, and weight.

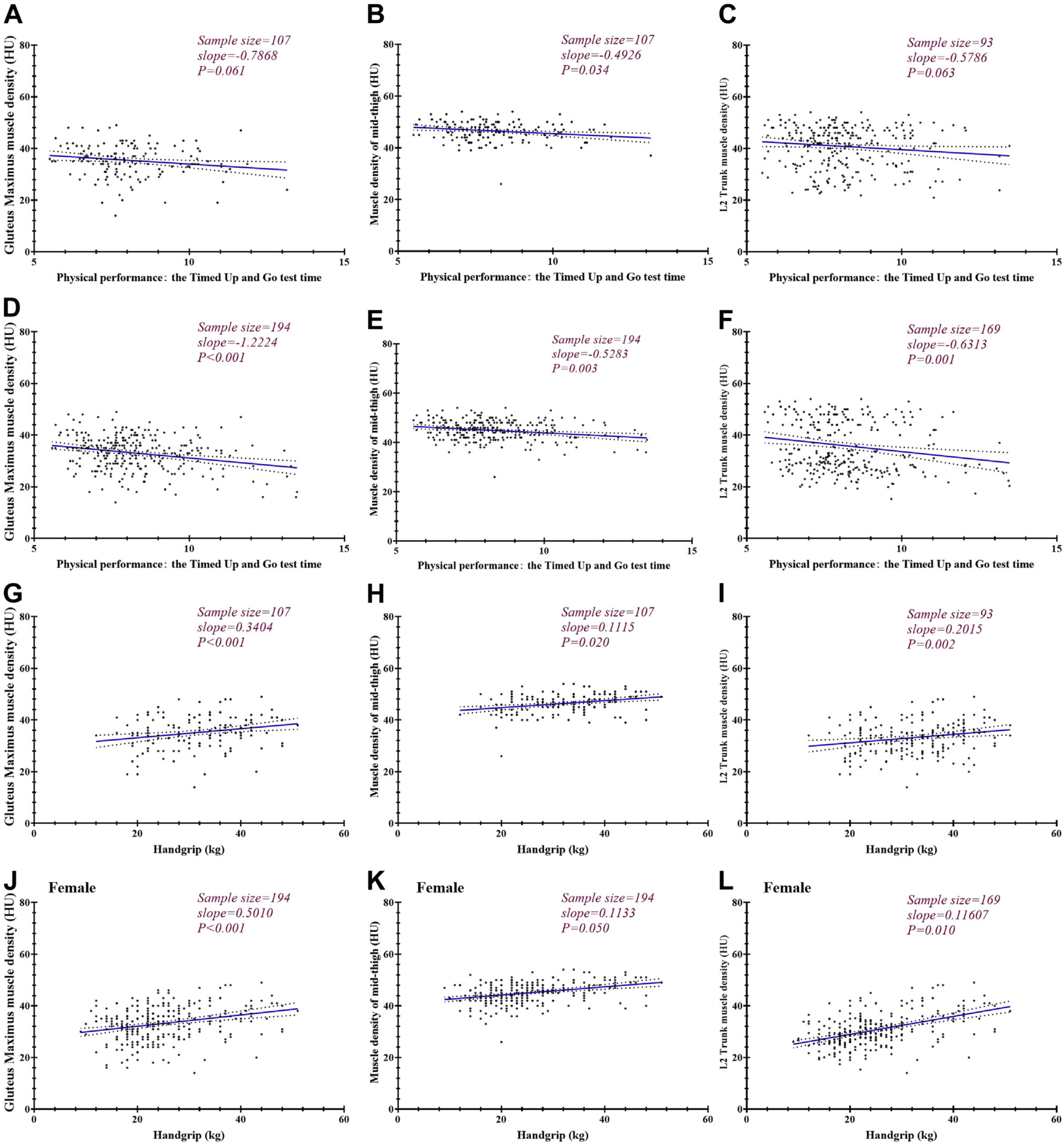

Fig. 3. Scatter plots for HGS and TUG by various densities at gluteus maximus, mid–thigh, and trunk muscles.

the trunk, hip, and mid-thigh. In our population of healthy older Chinese female individuals, an increase in muscle density (meaning a lower fat content) of the gluteus maximus and the paravertebral, but not of the mid-thigh muscles, was associated with an increase of HGS and a decrease of TUG (ie, of the time required performing the test). Apparently, trunk and hip muscle density is a factor for decreased balance and mobility. This finding is consistent with a recent study, which showed that increased intramuscular adipose tissue in the gluteal muscles, but not the thigh, was associated with increased gait variability and poorer balance.[24] This finding is also consistent with a study showing that in women, trunk muscle density but not size at the L2 level was associated with the Short Physical Performance Battery (SPPB) outcome ($\beta = 0.5$, confidence interval 0.01–0.98).[7] Similarly, the Health, Aging, and Body Composition study reported consistent associations.[25,26]

In contrast to other studies in older female participants,[2,11,12] we did not observe an association between mid-thigh muscle density and HGS or physical performance. In the Health, Aging, and Body Composition and the Age, Gene, Environment Susceptibility Reykjavik studies, researchers assessed the isokinetic strength of the knee extensors and SPPB, which were different from our TUG and HGS parameters. It is reasonable that site- matched muscle density and performance parameters may be more highly correlated than, for example, mid-thigh muscle density and HGS. Some of the discrepancies may also be explained by the population investigated in the respective studies. For example, there was no correlation between lean mass measured by DXA and TUG in an Asian population.[27] However, this requires further investigation as data are sparse and assessments vary across studies.

HGS is convenient and low cost, and frequently serves as a proxy for global muscle strength. However, the use of grip strength as a surrogate of overall muscle strength and function warrants caution, as some researchers have noted that grip strength is not associated with lower extremity strength and has moderate associations with physical performance and function.[28–30] What is more, a recent study implied HGS is largely, or at least to a significant high degree, a neuromuscular parameter consistent with the fact that HGS is more difficult to change by exercise than, for example, leg extension strength.[31] It is reasonable that no associations of HGS and mid-thigh muscle variables were observed in our study, and assessments of lower extremity strength may be more relevant to the assessment of thigh muscle.

Results for men were rather different, as neither muscle area nor density was associated with TUG, but muscle density of all muscles investigated was associated with HGS. Interestingly the Anderson study also did not find associations of L2 trunk muscle size and density with SPPB in men,[7] and, in a previous study, we observed a higher TUG with age in women, but no change in TUG with age in men.[14] This finding might partly explain the sex-related difference of the association of trunk muscle density and TUG.

The quantitative assessment of muscle properties is of increasing interest in the musculoskeletal field, both for research and for clinical practice. However, current measures of muscle size by CT and MRI or of lean mass by DXA do not adequately reflect the underlying pathophysiology of muscle strength and related functional outcomes. A good example highlighting these limitations is sarcopenia, because the relation between lean mass and functional outcome parameters remains low to moderate;[32] the recent European Working Group on Sarcopenia in Older People replaced “low muscle mass” by “low muscle strength” as a principal determinant of sarcopenia.[1]

The lipid infiltration of skeletal muscle appears to contribute to age-related decline in skeletal muscle function,[2] resulting in loss of muscle strength and reduced lower extremity performance, both of which confer increased risk of loss of mobility, falls, and skeletal fractures. Therefore, an important outcome of our study is that CT density of the gluteus maximus and of the trunk muscles was associated with muscle strength and functional outcome. These muscles can easily be assessed in routinely performed CT scans of the spine or hip, which may offer the opportunity for opportunistic screening, for example for sarcopenia.

More advanced image processing may improve the prediction of functional muscle outcomes from CT or MR scans. However, further research is required in order to exactly define these advanced parameters, to identify the appropriate anatomical locations for these measurements, and to standardize image acquisition protocols.

Several limitations exist in our study. A major limitation is the cross-sectional design, which prevented us from drawing conclusions about the causal associations between muscle size, muscle density, and functional impairments. Another limitation is the mismatch of the anatomic locations selected for density and strength assessments. In addition, we simply used HU values for the measurement of muscle density, which assumes an accurate water air calibration of the CT scanner. However, this is typically not the case and a phantom-based longitudinal monitoring water calibration is advised.[4,18]

Conclusions and Implications

In conclusion, our study shows that muscle density is more strongly associated with muscle strength than muscle size and that in women muscle density was also more strongly associated than muscle size with physical performance. Therefore, muscle density may represent a more clinically meaningful surrogate of muscle performance than muscle size. Muscle density measurements of trunk and gluteus muscles can be easily obtained from routine CT scans and, therefore, may become an important measurement to diagnose and screen for sarcopenia. The findings in our study may provide evidence for consensus on assessment methods of muscle quality in some clinical practice and research studies for the main sarcopenia working groups.

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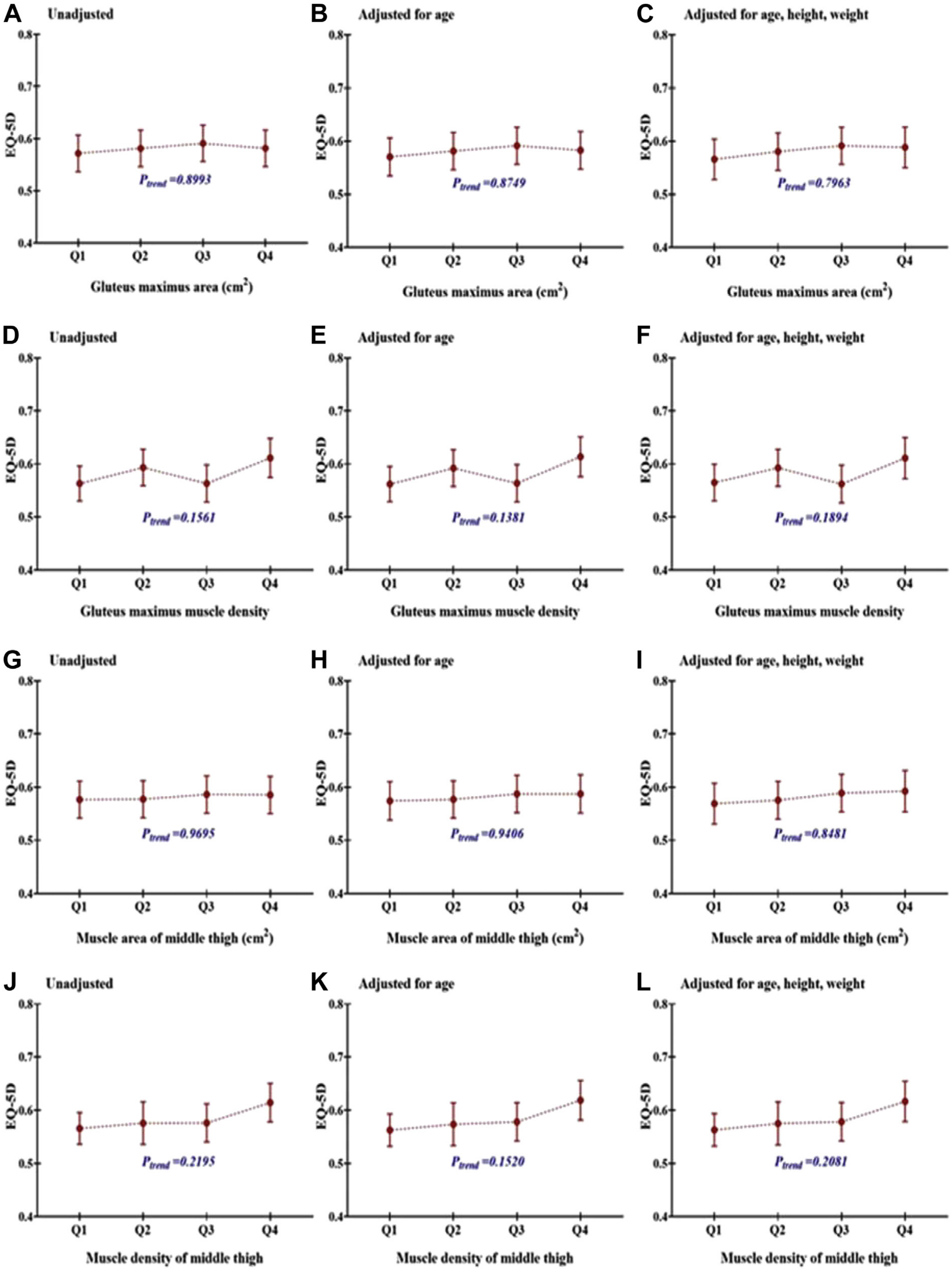
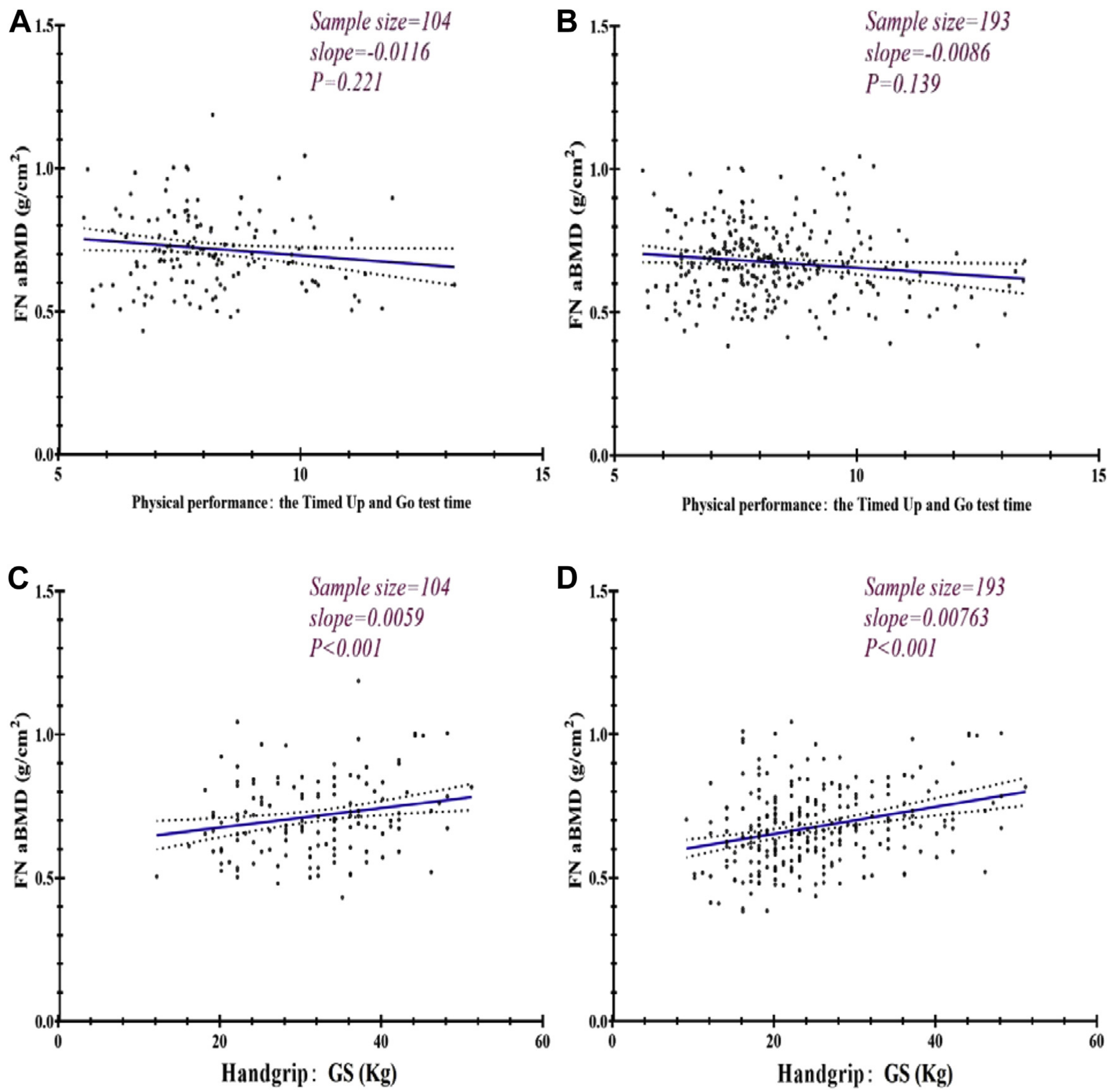


Supplementary Fig. 1. Forest plots for EQ–5D by quartile for muscle area and density.



Supplementary Fig. 2. Scatter plots for femoral neck aBMD by physical performance and HGS.

Supplementary Table 1
Comparisons Between Area and Density of Gluteus Medius and Minimus Muscle at Third Sacral (S3) and Non–Third Sacral (S4 and S5) Vertebrae Levels

Variables	S3 Level	Non–S3 Level	*P*
Area (cm^2)	40.3 ± 6.9	36.2 ± 8.0	.199
Density (HU)	42.1 ± 4.5	42.9 ± 4.2	.598