

Original Article

Toe Grasp Strength and Its Association with Muscle Mass and Calcaneal Bone Status in Young Adults: A Cross-Sectional Study

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Abstract

Objectives: The aim of this study was to investigate associations between toe grasp strength (TGS), skeletal muscle mass, and calcaneal bone status in young adults, and to determine whether TGS independently associates with musculoskeletal parameters. **Methods:** This cross-sectional study included 150 healthy young adults (118 males, 32 females; median age: 23 years). TGS was assessed using a standardized toe grasp dynamometer. Skeletal muscle mass was measured by bioelectrical impedance analysis (InBody 570), and calcaneal bone status was evaluated using quantitative ultrasound, expressed as standardized speed of sound (s-SOS). Associations between TGS, skeletal muscle index (SMI), and s-SOS were examined using correlation and multivariable regression analyses, with sex-stratified analyses. **Results:** Significant sex differences were observed in TGS, SMI, and s-SOS, with males showing higher values. In males, TGS was positively associated with both SMI and s-SOS. Multivariable analyses showed that higher TGS and younger age were independently associated with greater SMI and s-SOS in males. No significant associations were observed in females. **Conclusions:** In males, higher TGS is associated with greater skeletal muscle mass and better calcaneal bone status, suggesting that lower limb muscle strength reflects musculoskeletal status during early adulthood. Longitudinal studies are required to further clarify these associations.

Keywords: Calcaneal Bone Status, Musculoskeletal Health, Quantitative Ultrasound, Skeletal Muscle Index, Toe Grasp Strength

Introduction

Sarcopenia is a progressive decline in skeletal muscle mass, strength, and physical function associated with aging¹⁻⁵. It is linked to poor prognosis in various conditions, including cancer, cardiovascular disease, and osteoporotic fractures^{4,6-10}. Given its impact on overall health, early prevention, diagnosis, and treatment are essential.

Sarcopenia is also closely associated with reduced bone mineral density (BMD) in musculoskeletal disorders^{2,3}, emphasizing the interdependence between muscle and bone health. Current sarcopenia guidelines recommend diagnosing the condition based on criteria such as walking speed, hand grip strength, stand-up tests, leg circumference, and skeletal muscle mass^{4,11,12}, highlighting the crucial role of lower limb muscle strength in sarcopenia assessment. Toe grasp strength (TGS), a simple and non-invasive measure of lower limb muscle function, reflects the strength of multiple toe flexor muscles in the lower leg. TGS is influenced by factors such as height, weight, sex, and age, and it is recognized as a predictor of fall risk^{13,14}. Additionally, studies indicate that TGS can be improved through targeted muscle-strengthening interventions, further underscoring its importance in musculoskeletal health¹³⁻¹⁶.

Despite these insights, the relationship between TGS, whole-body skeletal muscle mass, and bone status remains

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poorly understood. Although previous research has explored general muscle strength and bone status, including BMD¹⁷⁻²⁰, few studies have specifically examined how toe muscle strength contributes to overall musculoskeletal health. Investigating this association is particularly relevant in young adults, as young adulthood represents a critical period for bone mass accumulation and muscle development^{21,22}.

Therefore, the purpose of this study is to investigate the association between TGS, skeletal muscle mass, and calcaneal bone status in healthy young adults. Clarifying these relationships may help characterize the role of lower limb muscle strength in musculoskeletal health during early adulthood, a critical period for the acquisition of peak muscle and bone mass.

Materials and Methods

Participants

This cross-sectional study was conducted between January and March 2023 and included 150 healthy young adult university students who had completed a clinical clerkship rotation in our department at a single university hospital. During the academic year, a total of 181 medical students (141 males and 40 females) rotated through our department. All eligible students were invited to participate in the study during the data collection period, and 150 students (118 males and 32 females) agreed to participate, yielding a participation rate of 82.9%. Inclusion criteria were: (1) enrollment as a university medical student, and (2) absence of subjective physical limitation. Exclusion criteria included the presence of internal medical comorbidities, musculoskeletal disorders, or any condition known to affect muscle or bone metabolism. The median age was 23 years (range, 21-39). Information regarding current sports participation (club or extracurricular activities) and history of ankle trauma (ankle sprain, peroneal tendon dislocation, Achilles tendon tear, etc) was obtained using a standardized questionnaire. Sports participation was defined as regular involvement in organized athletic or recreational activities.

TGS Measurement

TGS was assessed using the Takei T.K.K.3362 toe grasp dynamometer (Takei Scientific Instruments Co., Ltd., Japan). This device allows for a precise and reliable evaluation of toe flexor muscle strength^{23,24}. Participants were instructed to sit upright with their trunk in a vertical position, hip and knee joints flexed at 90 degrees, and ankle joint maintained in a neutral position. The grasp bar was carefully adjusted to align with the first metatarsophalangeal joint to ensure accurate and standardized measurements. TGS was measured twice for each foot, and the maximum value obtained from each side was recorded. The maximal strength value obtained from either foot was used as the representative TGS value for analysis, regardless of foot dominance. No familiarization

trials were performed prior to measurement, as high reliability has been reported^{23,24}.

Skeletal Muscle Mass Measurement

Skeletal muscle mass was assessed using the InBody 570 body composition analyzer (InBody Japan Co., Ltd., Japan). This device estimates body composition using bioelectrical impedance analysis (BIA), a quick, non-invasive, and widely used method that measures the electrical resistance of body tissues. Measurements were performed during daytime hours. Participants were instructed to void their bladder prior to measurement and to refrain from vigorous physical activity and alcohol consumption on the day of assessment. Although fasting was not required, all measurements were conducted under standardized conditions with participants in a standing position according to the manufacturer's protocol. These procedures were implemented to minimize the influence of hydration status on impedance measurements. BIA provides a reliable estimation of muscle mass, fat mass, and total body water, making it a valuable tool for evaluating sarcopenia and obesity in clinical and research settings. The following parameters were assessed: height, weight, body mass index (BMI), soft lean mass (SLM), percent body fat (PBF), basal metabolic rate (BMR), body cell mass (BCM), skeletal muscle index (SMI), and fat free mass index (FFMI). In this study, SMI (kg/m²) was calculated as appendicular skeletal muscle mass (ASM) divided by the square of the height. ASM was defined as the sum of the lean mass in both the arms and legs. SMI is a recognized diagnostic criterion for sarcopenia, with lower values indicating decreased muscle mass and potential impairment of physical function^{25,26}.

Bone Status Assessment using Quantitative Ultrasound

Bone status was evaluated using quantitative ultrasound (QUS) with the Benus EVO system (Nihon Kohden, Japan), a non-invasive and radiation-free technique. Measurement was performed at the right calcaneus, a skeletal site commonly used for bone evaluation due to its high trabecular bone content. All measurements were obtained with participants in a seated position, following the manufacturer's standardized protocol. QUS assesses bone status by measuring the speed of sound (SOS) of ultrasound waves passing through bone, which reflects density, structure, and elastic properties, rather than areal BMD measured in g/cm² by dual-energy X-ray absorptiometry (DXA). Nevertheless, previous studies have demonstrated a significant correlation between SOS values obtained from QUS and BMD measurements using DXA, the gold standard for osteoporosis assessment^{27,28}. In addition, the reproducibility and measurement precision of this device have been described as previously reported^{29,30}. Furthermore, standardized SOS (s-SOS) is often used to account for variations among different QUS devices and ensure consistency across studies. This measurement has

Table 1. Basic characteristics of the young adult participants.

	Total (n=150)	Male (n=118)	Female (n=32)	p value
Age (y) (median, IQR)	23 (23-25)	23 (23-25)	23 (23-24)	0.400
Height (cm) (median, IQR)	170 (164-175)	172 (169-176)	160 (157-162)	<0.001
Weight (kg) (median, IQR)	62 (55-70)	64 (59-71)	48.9 (46.7-56.1)	<0.001
BMI (kg/m ²) (median, IQR)	21 (20-23)	22 (20-24)	20 (19-22)	0.001
History of ankle trauma (yes) (n, %)	36 (24)	30 (25)	6 (19)	0.447
Current sports activity (yes) (n, %)	109 (73)	87 (74)	22 (69)	0.575
Ball sports (n, %)	25 (17)	25 (21)	0 (0)	
Racket sports (n, %)	29 (19)	22 (19)	7 (22)	
Track and field (n, %)	8 (5)	6 (5)	2 (6)	
Combat sports (n, %)	18 (12)	14 (12)	4 (13)	
Water sports (n, %)	12 (8)	8 (7)	4 (13)	
Golf (n, %)	17 (11)	12 (10)	5 (16)	
Data from InBody 570				
SLM (kg) (median, IQR)	49.0 (42.9-53.2)	51.4 (47.4-54.3)	36.1 (33.9-38.6)	<0.001
PBF (%) (median, IQR)	17.8 (13.6-22.2)	15.8 (13.0-20.6)	24.7 (21.0-27.7)	<0.001
BMR (kcal) (median, IQR)	1491 (1352-1588)	1547 (1452-1615)	1198 (1152-1369)	<0.001
BCM (kg) (median, IQR)	34.0 (29.7-37.2)	35.7 (33.0-38.3)	24.9 (23.4-26.8)	<0.001
SMI (kg/m ²) (median, IQR)	7.6 (6.8-8.0)	7.7 (7.3-8.1)	5.9 (5.7-6.4)	<0.001
FFMI (kg/m ²) (median, IQR)	17.8 (16.2-18.9)	18.1 (17.2-19.3)	15.1 (14.6-16.1)	<0.001
Data from QUS				
s-SOS (m/sec) (median, IQR)	1564 (1533-1590)	1574 (1538-1596)	1547 (1522-1563)	<0.001
YAM (%) (median, IQR)	100 (88-108)	101 (87-109)	96 (88-107)	0.750
TGS				
Right (kg) (median, IQR)	20.9 (IQR 17.0-25.4)	22.4 (IQR 19.0-26.7)	14.4 (IQR 10.8-18.5)	<0.001
Left (kg) (median, IQR)	21.1 (IQR 15.1-24.5)	21.6 (IQR 17.8-25.5)	14.5 (IQR 9.9-18.8)	<0.001

IQR, interquartile ranges; BMI, body mass index; SLM, soft lean mass; PBF, percent body fat; BMR, basal metabolic rate; BCM, body cell mass; SMI, skeletal muscle index; FFMI, fat free mass index; QUS, quantitative ultrasound; s-SOS, standardized-sound of speed; YAM, young adult mean; TGS, toe grasp strength. P values represent comparisons between male and female participants. Continuous variables were compared using the Mann-Whitney U test, and categorical variables were compared using the chi-square test. Sports activities were categorized as follows: Ball sports (e.g., baseball, soccer, basketball, volleyball, handball), Racket sports (e.g., tennis, badminton, table tennis), Track and field, Combat sports (e.g., kendo, karate, Japanese archery [kyudo]), Water sports (e.g., swimming, surfing), and Golf.

been shown to predict fracture risk effectively, making it a practical and accessible tool for musculoskeletal health evaluations^{31,32}. A single SOS measurement was obtained at the right calcaneus for each participant.

Statistical Analysis

All statistical analyses were performed using JMP (version 17, SAS Institute, Cary, NC, USA). Continuous variables were summarized as medians with interquartile ranges (IQR) to account for potential non-normal distributions. Categorical variables were presented as counts and percentages. Mann-Whitney U tests were used to compare continuous variables between the two groups, and categorical variables were compared using the chi-square test. Associations between TGS, SMI, and

s-SOS were examined using Spearman's rank correlation coefficients. Correlation analyses were performed for the total sample and stratified by sex. Multivariate regression analyses were conducted to examine the independent associations of TGS with SMI and s-SOS using continuous variables. Based on biological plausibility, the models were prespecified rather than selected by stepwise procedures. For the SMI model, age, sex, body mass index (BMI), current sports activity, and TGS were included as explanatory variables. For the s-SOS model, age, sex, BMI, SMI, and TGS were included. SMI was selected as the representative muscle mass indicator because it is the most commonly used parameter for sarcopenia²⁵, while other InBody indices were not included to avoid redundancy. Model assumptions were evaluated by inspection of residual plots for linearity and homoscedasticity, assessment of residual distributions for normality, and examination of multicollinearity using

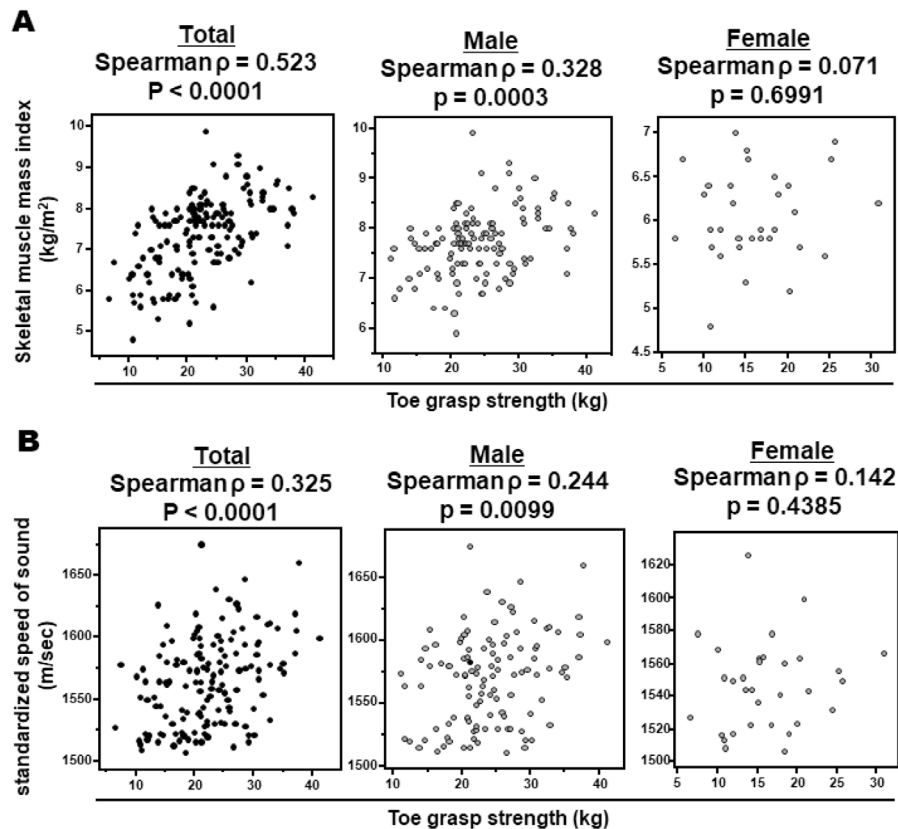


Figure 1. Associations between toe grasp strength and musculoskeletal parameters in young adults. Scatter plots showing the associations between maximum toe grasp strength and (A) skeletal muscle index and (B) calcaneal bone status assessed by standardized speed of sound. Spearman's rank correlation coefficients (ρ) and corresponding p values are shown for total, males and females, respectively. Each point represents an individual participant.

variance inflation factors. Regression coefficients, 95% confidence intervals (CI), p values, and coefficients of determination (R^2) were reported. Unstandardized regression coefficients (B) with 95% CI and standardized coefficients (β) were reported. A two-sided p value < 0.05 was considered statistically significant in all analyses.

Results

Basic Data of young adults

In the analysis of basic data from young adults, significant differences were observed between men and women across nearly all variables (Table 1). Current sports activity was reported by 73% of all participants, including 74% of men and 69% of women, with no significant difference between sexes ($p = 0.575$). A history of ankle-related trauma was present in 24% of the overall cohort (25% in men and 19% in women), and no significant sex difference was observed ($p = 0.447$). The InBody data were consistent with general population trends, showing typical patterns in

body composition. Specifically, the median SMI was 7.7 (IQR 7.3-8.1) in men and 5.9 (IQR 5.7-6.4) in women, reflecting greater muscle mass in men ($p < 0.001$). In terms of bone status, measured by s-SOS, the median value was 1574 (IQR 1538-1596) in men and slightly lower at 1547 (IQR 1522-1563) in women ($p < 0.001$). Maximum right TGS also differed between sexes, with a median of 22.4 kg (IQR 19.0-26.7) in men and 14.4 kg (IQR 10.8-18.5) in women ($p < 0.001$). These differences were statistically significant across all measured parameters.

Associations between TGS and musculoskeletal parameters

Associations between TGS and musculoskeletal parameters were examined using correlation analyses (Figure 1). When all participants were analyzed together, TGS showed a moderate positive correlation with SMI (Spearman's $\rho = 0.523$, $p < 0.001$) and a weaker but significant correlation with s-SOS at the calcaneus ($\rho = 0.325$, $p < 0.001$). When stratified by sex, TGS remained significantly correlated with SMI in men ($\rho = 0.328$, $p <$

Table 2. Factors associated with increased skeletal muscle index.

	B (95% confidence interval)	β	p value
Age	-0.020 (-0.045 – 0.005)	-0.063	0.109
Sex (female)	-0.612 (-0.702 – -0.521)	-0.545	<0.001
BMI	0.160 (0.136 – 0.184)	0.517	<0.001
Current sport activity (no)	-0.026 (-0.101 – 0.049)	-0.025	0.489
TGS	0.020 (0.009 – 0.030)	0.147	<0.001

B indicates unstandardized regression coefficients with 95% confidence intervals; β indicates standardized regression coefficients. BMI, body mass index; TGS, toe grasp strength.

Table 3. Factors associated with standardized speed of sound.

	B (95% confidence interval)	β	p value
Age	-2.471 (-4.447 – -0.496)	-0.205	0.015
Sex (female)	-1.315 (-12.292 – 9.662)	-0.031	0.813
BMI	0.868 (-2.045 – 3.780)	0.074	0.557
SMI	7.911 (-5.512 – 21.334)	0.209	0.246
TGS	1.081 (0.150 – 2.013)	0.212	0.023

B indicates unstandardized regression coefficients with 95% confidence intervals; β indicates standardized regression coefficients. BMI, body mass index; TGS, toe grasp strength; SMI, skeletal muscle index.

0.001), whereas no significant association was observed in women ($p = 0.071$, $p = 0.699$). Similarly, TGS was positively correlated with s-SOS in men ($p = 0.244$, $p = 0.010$), but not in women ($p = 0.142$, $p = 0.439$). These findings indicate that higher TGS is associated with greater skeletal muscle mass and better calcaneal bone status, particularly among male participants, supporting further multivariable analyses to account for potential confounding factors.

Multivariate Analysis of SMI and Bone Status

Multivariable linear regression analyses were performed to examine the associations between TGS and musculoskeletal parameters using continuous variables. When SMI was entered as the outcome variable, higher TGS ($B = 0.020$ [95% CI 0.009–0.030], $\beta = 0.147$, $p < 0.001$) was independently associated with greater SMI after adjustment for age, sex, BMI, and current sports activity (Table 2). Sex ($B = -0.612$ [95% CI -0.702–-0.521], $\beta = -0.545$, $p < 0.001$) and BMI ($B = 0.160$ [95% CI 0.136–0.184], $\beta = 0.517$, $p < 0.001$) were also significantly associated with SMI. The overall model explained a substantial proportion of variance in SMI ($R^2 = 0.820$). In the model with s-SOS as the outcome variable, higher TGS ($B = 1.081$ [95% CI 0.150–2.013], $\beta = 0.212$, $p = 0.023$) was significantly associated with greater s-SOS after adjustment for age, sex, BMI, and

SMI (Table 3). Age ($B = -2.471$ [95% CI -4.447–-0.496], $\beta = -0.205$, $p = 0.015$) was negatively associated with s-SOS. The explanatory power of this model was modest ($R^2 = 0.199$). These findings indicate that TGS is independently associated with both skeletal muscle mass and calcaneal bone status in young adults, even after accounting for relevant confounding factors. In the combined multivariable model including both sexes, the interaction term between TGS and sex (TGS \times sex) was not statistically significant for SMI ($p = 0.172$), indicating that the association between TGS and musculoskeletal parameters did not differ significantly by sex.

Grouping Based on Maximum TGS (secondary analysis)

As a secondary and exploratory analysis, participants were divided into two groups based on the median maximum TGS value obtained from either foot (males: <22.4 kg, $N = 52$; ≥ 22.4 kg, $N = 66$; females: <14.5 kg, $N = 14$; ≥ 14.5 kg, $N = 18$) (Table 4 and 5). A significant difference was found between the male groups in both SMI ($p = 0.005$) and s-SOS ($p = 0.019$) (Table 4). However, no significant differences were observed between the female groups (Table 5). The absence of significant findings in women may be attributable, at least in part, to the relatively small female sample size (118 males and 32 females), which may have limited the

Table 4. Data on maximum TGS in male divided into 2 groups based on median values (TGS<22.4 vs TGS≥22.4).

	Maximum TGS<22.4 (n=52)	Maximum TGS≥22.4 (n=66)	p value
Age (y) (median, IQR)	24 (23-25)	23 (22-25)	0.326
Height (cm) (median, IQR)	172 (169-176)	172 (169-176)	0.907
Weight (kg) (median, IQR)	64 (59-71)	65 (59-71)	0.466
BMI (kg/m ²) (median, IQR)	21 (20-23)	22 (20-24)	0.243
Trauma history around ankle (yes) (n, %)	13 (25)	17(26)	0.925
Current sports activity (yes) (n, %)	37 (71)	50 (76)	0.573
Data from InBody 570			
SLM (kg) (median, IQR)	50.0 (46.4-52.8)	51.9 (48.0-55.8)	0.013
PBF (%) (median, IQR)	17.2 (13.9-21.6)	14.7 (12.2-19.2)	0.033
BCM (kg) (median, IQR)	34.7 (32.2-36.7)	36.3 (33.6-39.4)	0.012
SMI (kg/m ²) (median, IQR)	7.7 (7.1-7.9)	7.9 (7.4-8.3)	0.005
FFMI (kg/m ²) (median, IQR)	17.7 (16.7-18.4)	18.5 (17.7-19.7)	<0.001
Data from QUS			
s-SOS (m/sec) (median, IQR)	1564 (1529-1586)	1578 (1553-1602)	0.019
YAM (%) (median, IQR)	99 (81-107)	102 (90-111)	0.074
TGS			
Right (kg) (median, IQR)	18.9 (15.3-20.7)	26.3 (23.8-30.1)	<0.001
Left (kg) (median, IQR)	17.2 (14.6-21.1)	25.1 (22.5-29.3)	<0.001

IQR, interquartile ranges; BMI, body mass index; SLM, soft lean mass; PBF, percent body fat; BMR, basal metabolic rate; BCM, body cell mass; SMI, skeletal muscle index; FFMI, fat free mass index; QUS, quantitative ultrasound; s-SOS, standardized-sound of speed; YAM, young adult mean; TGS, toe grasp strength.

Table 5. Data on maximum TGS in female divided into 2 groups based on median values (TGS<14.5 vs TGS≥14.5).

	Maximum TGS<14.5 (n=14)	Maximum TGS≥14.5 (n=18)	p value
Age (y) (median, IQR)	23 (23-24)	23 (23-24)	0.984
Height (cm) (median, IQR)	159 (155-161)	160 (157-163)	0.304
Weight (kg) (median, IQR)	48 (46-53)	51 (47-59)	0.403
BMI (kg/m ²) (median, IQR)	20 (18-21)	21 (19-22)	0.254
Trauma history around ankle (yes) (n, %)	2 (14)	4 (22)	0.568
Current sports activity (yes) (n, %)	10 (71)	12 (67)	0.773
Data from InBody 570			
SLM (kg) (median, IQR)	35.2 (33.7-38.5)	37.1 (34.0-38.9)	0.459
PBF (%) (median, IQR)	22.5 (20.4-26.9)	25.9 (22.5-28.5)	0.262
BCM (kg) (median, IQR)	24.4 (23.1-26.4)	25.6 (23.4-27.2)	0.393
SMI (kg/m ²) (median, IQR)	5.9 (5.7-6.4)	6.0 (5.8-6.6)	0.731
FFMI (kg/m ²) (median, IQR)	15.1 (14.7-15.5)	15.1 (14.5-16.3)	1.000
Data from QUS			
s-SOS (m/sec) (median, IQR)	1544 (1517-1555)	1552 (1529-1563)	0.414
YAM (%) (median, IQR)	91 (86-102)	103 (87-108)	0.393
TGS			
Right (kg) (median, IQR)	10.8 (9.7-12.3)	18.4 (15.7-21.8)	<0.001
Left (kg) (median, IQR)	9.5 (7.1-12.3)	17.5 (15.1-20.8)	<0.001

IQR, interquartile ranges; BMI, body mass index; SLM, soft lean mass; PBF, percent body fat; BMR, basal metabolic rate; BCM, body cell mass; SMI, skeletal muscle index; FFMI, fat free mass index; QUS, quantitative ultrasound; s-SOS, standardized-sound of speed; YAM, young adult mean; TGS, toe grasp strength.

statistical power. In addition, no significant differences in current sports participation were found between students with higher (male 76%; female 67%) and lower TGS (male 71%; female 71%) (male: $p = 0.573$; female: $p = 0.773$) (Table 4 and 5). To further explore the potential influence of sports activity, subgroup analyses stratified by sports activity status are presented in Supplementary Tables 1 and 2. Among male students, those with sports activity were slightly younger than those without (median 23 vs 24 years old, $p = 0.033$), but no other significant differences were observed in SMI ($p = 0.596$), s-SOS ($p = 0.069$), or TGS (right: $p = 0.465$; left: $p = 0.847$). Among female students, no significant differences were observed between the sports activity groups.

Discussion

In this study of young adults, TGS was found to be significantly associated with skeletal muscle mass assessed by InBody and with calcaneal bone status indicated by s-SOS, particularly among male participants. Multivariate analysis revealed that higher TGS was independently associated with greater muscle mass and more favorable bone status after adjustment for relevant covariates. These findings suggest that lower limb function, including toe strength, reflects aspects of musculoskeletal status during early adulthood, a critical period for muscle and bone development.

SMI is a well-established measure that reflects total muscle mass in the body³³⁻³⁵. It serves as an important indicator of muscle strength, which plays a crucial role in physical function, including standing, walking, and jumping^{36,37}. TGS, which involves the toe flexor muscles, is critical for maintaining stability and balance³⁸. Reduced TGS is particularly concerning in elderly populations³⁹, as it is strongly associated with an increased risk of falls¹⁴. This relationship is well-documented in the literature, as reduced muscle strength, including TGS, is frequently linked to higher rates of functional decline, loss of mobility, and dependency in daily activities⁴⁰. Studies have shown that lower body strength, including TGS, is a strong associated factor of physical performance and the ability to perform daily activities independently^{23,39,41,42}. Although most previous studies have focused on older adults, the present study demonstrates that a similar association between TGS and skeletal muscle mass is already observable in healthy young adults, particularly among men. Our findings suggest that TGS reflects aspects of overall muscle status during early adulthood, a critical period for muscle development, rather than serving as a direct indicator of functional decline or sarcopenia. Given its simplicity and non-invasive nature, TGS may be a practical measure for assessing lower limb muscle function when interpreted alongside established indicators such as SMI. However, its role should be considered complementary rather than diagnostic. The potential influence of sports activity was also examined in this cohort. Although many participants

regularly engaged in sports, current sports participation did not differ between students with stronger and weaker TGS. Subgroup analyses further showed that, among male students, those who participated in sports were slightly younger, but no significant differences were observed in SMI, s-SOS, or TGS. Similarly, no associations between sports activity and musculoskeletal parameters were identified among female students. These findings suggest that the observed associations between TGS, muscle mass, and bone status were not substantially confounded by current sports participation in this cohort. According to the Asian Working Group for Sarcopenia (AWGS) criteria, low muscle mass is defined as an SMI <7.0 kg/m² in men and <5.7 kg/m² in women^{25,26}. In the present cohort, the median SMI was 7.7 kg/m² (IQR 7.3–8.1) in men and 5.9 kg/m² (IQR 5.7–6.4) in women. Although a small number of participants fell below the AWGS cut-off values, the majority of the cohort did not meet the criteria for low muscle mass. Therefore, the present findings primarily reflect inter-individual variation in muscle mass within a predominantly non-sarcopenic young adult population, rather than sarcopenia *per se*.

The relationship between muscle strength and BMD has been extensively studied across various populations^{17,43-47}. Skeletal muscle mass and strength are believed to influence bone health by generating mechanical loads that stimulate bone remodeling, leading to a positive association with BMD^{44,45}. Furthermore, progressive resistance training has been shown to effectively increase lower limb muscle strength and femoral BMD in older adults, highlighting the close interaction between muscle and bone tissues^{48,49}. Although these mechanisms have been well documented mainly in middle-aged and older populations, the present study demonstrates that an association between muscle strength and bone status is also observable in healthy young adults. Importantly, bone status in this study was assessed using QUS. While QUS-derived s-SOS correlates with areal BMD measured by DXA, it does not directly represent areal BMD expressed in g/cm². Rather, s-SOS reflects composite bone characteristics, including density, microarchitecture, and elasticity. In addition, clinical cut-off values for osteoporosis differ between QUS and DXA, and QUS should be interpreted primarily as a screening or bone status assessment tool rather than a diagnostic modality. Accordingly, the present findings indicate an association between TGS and calcaneal bone status, rather than definitive BMD or fracture risk. In this cohort of young adults, higher TGS was associated with higher s-SOS values, suggesting that toe muscle strength reflects aspects of musculoskeletal status during early adulthood. These results support the concept that lower limb muscle strength is linked to bone status even during the period of peak bone mass acquisition. Young adulthood represents a critical period for achieving peak muscle and bone mass^{50,51}, which may influence physical function later in life. From this perspective, the present findings should be interpreted as hypothesis-generating, and longitudinal

studies are required to determine whether such associations translate into long-term clinical outcomes.

Uritani et al. reported mean TGS values of approximately 16.9–17.1 kg in males and 10.4–11.5 kg in females in their 20s and 30s²³, while Suwa et al. reported a mean TGS of 21.8 kg in males in their 30s⁵². In the present study, the median maximal TGS was 22.4 kg in males and 14.5 kg in females, which is consistent with these previous reports and supports the validity of our measurements. Although TGS is influenced by body size, additional analyses using body weight-normalized TGS did not demonstrate significant associations with skeletal muscle mass or calcaneal bone status in the present cohort (data not shown). Therefore, absolute TGS values adjusted for BMI were used in the multivariate analyses. Previously reported that while weight-normalized TGS differed between sexes, no significant differences were observed between individuals in their 20s and 30s²³, suggesting that normalization by body weight may reduce age-related variability in younger populations. Given that the present study predominantly included young adults, this may partly explain why body weight-normalized TGS did not show significant associations in our analysis.

In this study, significant associations between TGS and both SMI and calcaneal bone status assessed by s-SOS were observed in male participants, whereas no significant associations were detected in females. These results indicate that the observed relationships were primarily driven by male participants. The absence of significant associations in women is likely attributable to methodological factors rather than a true lack of relationship. Female participants were fewer in number and exhibited a relatively narrow BMI distribution (median 20, IQR 19–22), with many being lean, which may have limited variability in muscle mass and bone status and reduced statistical power. In addition, voluntary participation may have introduced selection bias, potentially underrepresenting women with a wider range of body compositions. Although biological sex differences in muscle–bone interactions may exist, the present cross-sectional data are insufficient to distinguish biological mechanisms from sample-related limitations. Therefore, sex-specific interpretations should be considered exploratory, and further studies including larger and more diverse female samples are warranted.

Several limitations should be acknowledged. First, the sample size, particularly for female participants, was relatively small, which may have limited statistical power to detect sex-specific associations. Although sex-stratified analyses were performed, subtle sex-dependent differences cannot be excluded. Second, participants were recruited from a single medical school. Although students rotated through the department throughout the academic year, the study population represents a single-center, convenience sample of medical students and may not fully reflect the general young adult population. Participation was voluntary, which may have introduced selection bias toward individuals who were more health-conscious or physically active. Therefore, the generalizability of

the findings to young adults with different educational, occupational, or lifestyle backgrounds may be limited. Third, this was a cross-sectional study, therefore, causal relationships or temporal sequences between TGS, skeletal muscle mass, and bone status cannot be established. Longitudinal studies are required to determine whether higher TGS contributes to greater muscle and bone accrual or merely reflects underlying musculoskeletal status. Fourth, several potentially important covariates were not assessed, including dietary intake (e.g., protein and calcium), vitamin D status, smoking habits, hormonal factors, and, in women, menstrual history. These factors are known to influence muscle mass and bone status, and residual confounding related to these unmeasured variables cannot be excluded. Fifth, skeletal muscle mass and bone status were assessed using BIA and QUS rather than DXA. Although both BIA and QUS are non-invasive and practical tools and have been shown to correlate with DXA-derived measures⁵³, they do not provide the same level of precision or diagnostic capability. In particular, QUS-derived s-SOS reflects bone status rather than areal BMD, and clinical cut-off values differ between methods. Sixth, hand grip strength, a widely used indicator of muscle strength and bone health, was not measured; therefore, we were unable to directly compare TGS with hand grip strength. Seventh, sports activity was assessed only as a binary variable (present/absent), without detailed information on exercise type, intensity, frequency, or duration. Given the important role of physical activity in musculoskeletal health, residual confounding related to unmeasured aspects of sports participation cannot be excluded. Although a TGS \times sex interaction term was examined in a combined multivariable model and was not statistically significant, the limited number of female participants may have reduced the ability to detect interaction effects. Finally, the assessment of functional outcomes such as balance, gait, and mobility was not included in this study. Future research should incorporate these measures to better understand how TGS and muscle mass impact functional performance and daily living capabilities in different age groups.

In conclusion, our findings support the idea that increased TGS in young adult males is associated with greater skeletal muscle mass and calcaneal bone status, suggesting that TGS reflects lower limb muscle function and overall musculoskeletal status in this population. Future research, particularly longitudinal studies with larger and more diverse populations, is needed to further clarify these relationships and to better understand the potential relevance of TGS across the life course.

Ethics Approval

This study was approved by the Ethics Committee of Kyushu University Hospital (approval number: 22276-00) and was conducted in accordance with the Declaration of Helsinki (1964) and its later amendments.

Consent to Participate

Written informed consent was obtained from all participants prior to participation.

Authors' Contributions

Conceptualization, TF, MK, RY, NY, and YN; Acquisition of data, TF and MK; Analysis of data, TF; Interpretation of data, TF; Original draft preparation TF; Writing–reviewing and editing, TF; Supervision, TF, RY, NY, and YN; All authors approved the final version of the manuscript.

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Supplemental Table 1. Baseline characteristics of young adult male participants (n=118) stratified by current sports activity (No/Yes).

	Current sports activity (No) (n=31)	Current sports activity (Yes) (n=87)	p value
Age (y) (median, IQR)	25 (23-28)	23 (23-24)	0.033
BMI (kg/m ²) (median, IQR)	21 (20-26)	22 (20-23)	0.910
Trauma history around ankle (yes) (n, %)	4 (13)	26 (30)	0.062
Data from InBody 570			
SLM (kg) (median, IQR)	48.3 (44.9-54.4)	51.5 (48.2-54.3)	0.197
PBF (%) (median, IQR)	17.8 (13.0-21.8)	15.5 (12.9-19.9)	0.118
BCM (kg) (median, IQR)	33.8 (31.1-38.4)	35.8 (33.7-38.3)	0.165
SMI (kg/m ²) (median, IQR)	7.6 (7.1-8.1)	7.7 (7.3-8.1)	0.596
FFMI (kg/m ²) (median, IQR)	18.0 (16.5-19.4)	18.2 (17.3-19.3)	0.642
Data from QUS			
s-SOS (m/sec) (median, IQR)	1563 (1529-1582)	1577 (1543-1599)	0.069
TGS			
Right (kg) (median, IQR)	22.1 (17.6-25.6)	22.4 (19.5-27.1)	0.465
Left (kg) (median, IQR)	21.2 (16.8-27.6)	21.8 (18.1-24.6)	0.847

IQR, interquartile ranges; BMI, body mass index; SLM, soft lean mass; PBF, percent body fat; BMR, basal metabolic rate; BCM, body cell mass; SMI, skeletal muscle index; FFMI, fat free mass index; QUS, quantitative ultrasound; s-SOS, standardized-sound of speed; TGS, toe grasp strength.

Supplemental Table 2. Baseline characteristics of young adult female participants (n=32) stratified by current sports activity (No/Yes).

	Current sports activity (No) (n=10)	Current sports activity (Yes) (n=22)	p value
Age (y) (median, IQR)	24 (23-25)	23 (23-24)	0.322
BMI (kg/m ²) (median, IQR)	19 (18-22)	20 (19-21)	0.440
Trauma history around ankle (yes) (n, %)	2 (20)	4 (18)	0.903
Current sports activity (yes) (n, %)	37 (71)	50 (76)	0.573
Data from InBody 570			
SLM (kg) (median, IQR)	35.7 (34.0-38.0)	36.6 (33.8-38.9)	0.776
PBF (%) (median, IQR)	23.8 (20.3-26.4)	25.3 (21.0-28.5)	0.515
BCM (kg) (median, IQR)	24.7 (23.4-26.2)	25.2 (23.4-27.2)	0.699
SMI (kg/m ²) (median, IQR)	5.9 (5.6-6.5)	6.0 (5.8-6.4)	0.438
FFMI (kg/m ²) (median, IQR)	14.9 (14.1-16.4)	15.1 (14.7-15.8)	0.360
Data from QUS			
s-SOS (m/sec) (median, IQR)	1542 (1521-1571)	1549 (1522-1563)	0.935
TGS			
Right (kg) (median, IQR)	14.3 (10.4-18.1)	14.9 (11.6-19.1)	0.405
Left (kg) (median, IQR)	15.1 (8.4-17.7)	14.3 (10.3-19.3)	0.655

IQR, interquartile ranges; BMI, body mass index; SLM, soft lean mass; PBF, percent body fat; BMR, basal metabolic rate; BCM, body cell mass; SMI, skeletal muscle index; FFMI, fat free mass index; QUS, quantitative ultrasound; s-SOS, standardized-sound of speed; TGS, toe grasp strength.