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Original Article

Low Phase Angle as a Clinical Marker of Sarcopenia in Older Adults: Exploring the Structure–Quality–Strength–Mobility (SQSM) Framework

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Abstract

Objectives: This study aimed to evaluate phase angle (PhA) as a clinical marker of sarcopenia within the multidimensional Structure–Quality–Strength–Mobility (SQSM) framework and to compare its associations with muscle strength and physical performance against sarcopenia defined by appendicular skeletal muscle mass index (ASMI). **Methods**: A cross-sectional study was conducted on 87 older adults (mean age 68.8 years; 70.1% female) recruited into a structured exercise program. PhA and ASMI were measured via bioelectrical impedance analysis in the program's final week. Muscle strength and physical performance were measured using the Asian Working Group for Sarcopenia definitions. The SQSM-operationalised definition(OD) of sarcopenia was classified as low PhA combined with either low handgrip strength (HGS) or gait speed(GS). Logistic regression assessed associations. **Results**: Phase angle ≤4.25° was associated with low HGS (OR = 2.51, p = 0.058), GS (OR = 3.96, p = 0.010), and falls (OR = 4.20, p = 0.024). SQSM-OD of sarcopenia showed higher prevalence and stronger association with falls (OR = 5.77, p = 0.008) than ASMI-defined sarcopenia. **Conclusion**: PhA was associated with low muscle strength, gait speed and falls supporting its role as a marker of muscle quality. SQSM-OD identified more at-risk individuals highlighting the utility of incorporating muscle quality into sarcopenia assessment.

Keywords: Phase angle, Muscle function, Muscle Quality, Sarcopenia, SQSM framework

Introduction

Sarcopenia is defined as an age-related decline in muscle mass and function. Although low muscle mass is a key criterion for diagnosing sarcopenia, measuring it in clinical practice remains challenging due to limited availability of practical tools[1]. Magnetic resonance imaging (MRI) and computed tomography (CT) are considered the gold standard for accurately assessing skeletal muscle mass. However, it remains largely confined to research settings due to their cost and technical complexity[2]. The D_3-creatine dilution method has emerged as a highly accurate and minimally invasive alternative technique that directly reflects skeletal muscle creatine pool size, serving as a promising surrogate for true muscle mass. Nevertheless, its routine application is limited by similar logistical and cost-related barriers, reinforcing the need for more clinically feasible tools[3]. Consequently, more widely available alternatives in clinical settings include dual-energy X-ray absorptiometry (DXA) and bioelectrical impedance analysis (BIA). While DXA estimates lean soft tissue directly, BIA estimates fat-free mass from which skeletal muscle mass is derived

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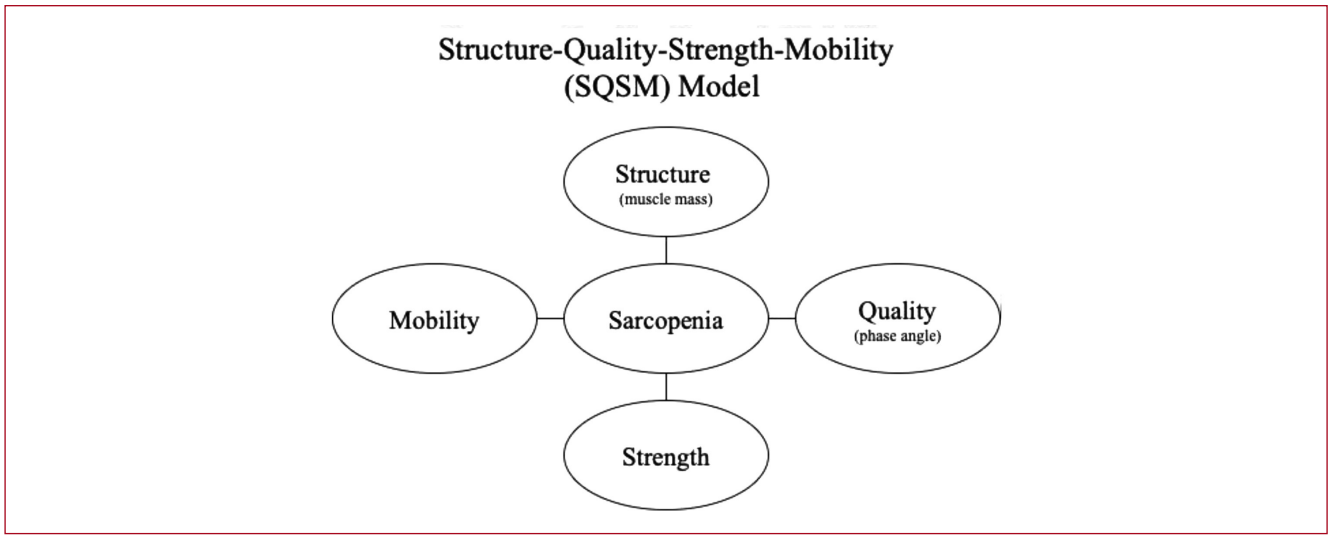

Figure 1. Structure–Quality–Strength–Mobility (SQSM) conceptual model for sarcopenia assessment.

using prediction equations[4]. BIA primarily estimates fat-free mass (FFM) which includes muscle, water, organs and bone. DXA, on the other hand, estimates lean soft tissue (LST) typically defined as all non-fat, non-bone tissue including non-contractile components such as organs and extracellular fluid[4]. These compartments do not exclusively reflect skeletal muscle, which may partly explain the weak correlations observed between DXA- and BIA-derived muscle estimates and functional outcomes such as mobility impairment, falls and mortality[5-7]. Hence, some sarcopenia working groups have shifted away from emphasising low muscle mass in their diagnostic criteria[8,9].

The recently published conceptual definition by Global Leadership Initiative in Sarcopenia (GLIS) reinforces the role of muscle mass in sarcopenia diagnosis[10]. However, given its challenges in measuring it practically, the emergence of muscle quality as an indicator has been mooted by both the European Working Group on Sarcopenia in Older People (EWGSOP) and Asian Working Group for Sarcopenia (AWGS), though neither have yet established standardized methods for evaluation[11,12].

Muscle quality broadly refers to features beyond muscle mass, including morphology and functional properties. Morphological aspects include fat infiltration, the ratio of contractile to non-contractile tissue, muscle echogenicity, water content and muscle cross-sectional area[13]. Given the diverse aspects that the term covers, GLIS has advised caution in its use and emphasized the need to clearly define 'muscle quality' in research, particularly when describing assessment tools[10].

Among the proposed surrogate markers, Bioelectrical impedance analysis-derived phase angle (BIA-PhA) has emerged as a particularly promising and accessible indicator of muscle quality[14]. Phase angle (PhA) reflects cell membrane integrity. It is calculated from resistance and reactance values and no predictive equations are required, unlike bioelectrical impedance analysis-derived appendicular skeletal muscle mass (BIA-ASM) that is normally used in sarcopenia diagnosis[14]. A reduction in PhA typically reflects a decrease in reactance due to reduced muscle mass and an increase in resistance, often associated with increased fat mass[14]. A recent meta-analysis conducted by Zhang et al among the Asian population demonstrated that low PhA has moderate diagnostic accuracy in screening for sarcopenia compared to other tools highlighting its potential value for diagnostic markers[15].

To build on this, we propose a multidimensional conceptual framework called the Structure–Quality–Strength–Mobility (SQSM) model to better reflect the complex physiological characteristics underlying sarcopenia. This model incorporates four interrelated domains: (1) Structure, referring to muscle mass when available; (2) Quality, represented by phase angle for cellular integrity; (3) Strength measured by grip strength; and (4) Mobility assessed through performance-based tests such as gait speed. An overview of the SQSM model is illustrated in Figure 1.

The SQSM model is intended as a conceptual framework rather than a diagnostic tool. It is designed to allow flexibility in sarcopenia assessment, and is particularly relevant in settings where accurate muscle mass assessment is limited.

For instance, phase angle is a marker of cellular integrity that partially reflects both structural and qualitative muscle changes which can serve as a practical surrogate in such contexts. By emphasizing biological and clinical relevance over rigid thresholds, the SQSM model supports a more adaptable, easily accessible and feasible approach to identifying and understanding sarcopenia across diverse clinical and research environments.

Participants in this study were recruited from The Resistance, Strength, and Balance Training (ReST) study, a structured exercise programme using Muslim Prayer Movements and Terminology which was rolled out as a targeted intervention for sarcopenia to improve exercise adherence and tolerability. This study explores the utility of low phase angle as a clinical marker of sarcopenia and assesses how it aligns with other sarcopenia components using the SQSM lens.

Materials and Methods

Study Design and Setting

This is a cross-sectional ancillary study of participants enrolled into the ReST program. Bioelectrical impedance analysis was assessed using the Tanita MC-780MA. Data collection was conducted at the end of the 12-week programme due to limited accessibility of the BIA machine. This study aimed to explore the associations between BIA-derived phase angle, muscle strength, and physical performance among older adults using the SQSM framework as a conceptual lens. To operationalise this, a working model was applied in which SQSM was defined as low phase angle combined with either low handgrip strength or slow gait speed. Additionally, the findings were compared with the AWGS 2019 definition (low appendicular skeletal muscle mass/height squared and poor muscle strength or physical performance) to highlight potential differences in interpretation[12].

Participants

Community-dwelling older adults aged ≥60 years who were generally healthy and independent in activities of daily living (Katz score 6) were invited to participate in the ReST programme and were included in this ancillary study. Participants with major illnesses, recent surgery (<1 year), acute illnesses, or limited mobility preventing them from participating in the programme were excluded. In addition, individuals with cardiac devices were excluded from BIA assessment. Of the 89 participants enrolled, those aged ≥80 years (n = 2) were excluded from subgroup analyses due to small numbers.

Anthropometry and BIA Measurement

Standing height was measured using a measuring tape. Body composition was assessed using the Tanita MC-780 MA (Japan), a multifrequency BIA device with 8 electrodes. Participants were instructed to stand barefoot on the scale and hold the hand grips with arms apart from the body. The following BIA-derived parameters were collected: weight, resistance, reactance, segmental phase angle (PhA) obtained at 50khz, and appendicular skeletal muscle mass index (ASMI).

To determine clinically relevant thresholds for low phase angle (PhA), three cut-off values were explored. An ROC-derived optimal cut-off of 4.25° based on its association with low appendicular skeletal muscle mass (ASM/height2) from our study population. In addition to our study-specific threshold, we applied previously reported phase angle thresholds of 4.54° and 5.25°, which represent the lower and upper limits of a reference range reported in a meta-analysis of 12 studies[15]. These values were selected to capture the spectrum of previously proposed cut-offs associated with adverse outcomes in older adults.

Low appendicular skeletal muscle mass index was defined using the ratio of appendicular skeletal muscle mass to height squared (ASM/height^2) cut-off values: <7.0 kg/m^2 for men and <5.8 kg/m^2 for women, in accordance with AWGS 2019 guidelines[12].

Muscle Strength and Physical Performance

Handgrip strength was assessed with the Jamar Plus digital hand dynamometer on the dominant hand, with two trials performed and the maximum value was taken[12]. Low muscle strength was defined as <28 kg for men and <18 kg for women[12]. Gait speed was measured by timing participants as they walked 6 metres at their usual pace. A gait speed <1.0 m/s was classified as low physical performance[12].

Statistical Analysis

Data was analysed using R Studio (MacOS). Descriptive statistics were used to summarise participant characteristics.

To determine an outcome-based cutoff for low phase angle in this study population, a receiver operating characteristic (ROC) curve was generated using low appendicular skeletal muscle mass (ASM/height^2) as the reference standard. The optimal threshold was identified using the Youden Index, which maximises the sum of sensitivity and specificity.

Logistic regression was used to examine the associations between different phase angle cutoffs (≤4.25°, ≤4.54°, ≤5.25°) and the outcomes of low muscle strength, slow gait speed, and history of falls. All models were adjusted for age group, BMI, and sex. Interaction terms between phase angle and each covariate (age, BMI, and sex) were tested to assess effect modification. A significant interaction was observed between phase angle and age for the outcome of low muscle strength (p = 0.045), therefore all models were stratified by age group to ensure consistency across analyses. No significant interactions were observed for BMI

Variable	Male (n = 26)	Female (n = 61)	p-value[1]	Hedges' g (95% CI)
Sex Distribution (%)	29.9%	70.1%	—	
Age (years)	70.7 ± 5.3	68.0 ± 5.2	0.028	0.53 (0.06 – 0.99)
BMI (kg/m²)	26.6 ± 4.3	29.3 ± 5.6	0.018	-0.50 (-0.96 – -0.04)
ASM/height² (kg/m²)	7.67 ± 1.13	6.70 ± 0.72	<0.001	1.12 (0.63 – 1.60)
Phase Angle (°)	4.48 ± 0.71	4.53 ± 1.33	0.800	-0.05 (-0.50 – 0.41)
Handgrip Strength (kg)	30.05 ± 7.44	21.66 ± 5.68	<0.001	1.33 (0.83 – 1.82)
Gait Speed (m/s)	1.02 ± 0.21	0.95 ± 0.18	0.135	0.37 (-0.09 – 0.83)

[1]p-value is presented only for phase angles and gait speed where gender-related differences are uncertain. Variables with well-established sex differences were not tested for statistical significance. Abbreviations: BMI = Body Mass Index; ASM = Appendicular Skeletal Muscle

Table 1. Sex-based descriptive statistics of key variables.

Outcome	≤ 4.25° OR (95% CI), *p*	≤ 4.54° OR (95% CI), *p*	≤ 5.25° OR (95% CI), *p*
Low strength	2.51 (0.98 – 6.59), 0.058	2.87 (1.13 – 7.74), 0.030	15.3 (1.85 – 200.6)[1], 0.006[a]
Gait speed <1.0m/s²	3.96 (1.44 – 12.0), 0.010[b]	2.21 (0.90 – 5.54), 0.086	0.92 (0.22 – 3.57), 0.904
Falls	4.20 (1.25 – 15.7), 0.024[b]	1.35 (0.43 – 4.48), 0.609	0.98 (0.21 – 7.16), 0.984
Sensitivity	83.3%	83.3%	100.0%
Specificity	64.2%	45.7%	13.6%

[1]Odds ratio are from Firth logistic regression. Adjusted for age group, sex and BMI. OR = Odds ratio; CI = Confidence Interval. [a]: p <0.05 using Firth logistic regression. [b]: p<0.05 using logistic regression.

Table 2. Associations Between Phase Angle Cutoffs and Functional Outcomes with Corresponding Sensitivity and Specificity.

Prevalence was compared between SQSM-operationalised definition (OD) of sarcopenia and AWGS-defined sarcopenia. Both definitions were further assessed for their associations with falls using logistic regression. Agreement between definitions was evaluated using Cohen's kappa and McNemar's test. Odds ratios (ORs) and 95% confidence intervals (CIs) were reported, with p-values <0.05 considered statistically significant. Given the limited sample size (n=87), presence of small and uneven subgroups, Hedges' g was used to calculate effect sizes for continuous variables to ascertain the clinical strengths of observed associations. These were reported with 95% confidence intervals where appropriate.

Results

Participant characteristics

A total of 87 participants (mean age of 68.8 years, 70.1% female) were included. Table 1 presents sex-based descriptive statistics. Males exhibited higher ASM/height² (7.67 ± 1.13kg/h² vs 6.70 ± 0.72kg/h²) and greater (p=0.800) and gait speed (p=0.135) were comparable between sexes with no statistically significant difference. The full study sample had a mean gait speed of 0.97 ± 0.20 m/s and mean phase angle of 4.52 ± 1.18 °.

Association of Phase Angle Cutoffs with Muscle Function, Falls, and Diagnostic Accuracy

Table 2 presents the association between three phase angle (PhA) cutoffs and muscle function outcomes and falls adjusted for age, sex and BMI. Using a cutoff of ≤4.54°, low phase angle was significantly associated with low muscle strength (OR = 2.87; 95% CI: 1.13–7.74; $p = 0.030$), while a cutoff of ≤5.25° demonstrated a stronger association (OR = 15.3; 95% CI: 1.85–200.6; $p = 0.006$). In contrast, the ≤4.25° cutoff showed a borderline association with low strength (OR = 2.51; 95% CI: 0.98–6.59; $p = 0.058$).

For slow gait speed (<1.0 m/s), only the ≤4.25° cutoff showed a statistically significant association (OR = 3.96; 95% CI: 1.44–12.0; $p = 0.010$), whereas the 4.54° and 5.25° cutoffs were not significant ($p = 0.086$ and

PhA Cutoff	N (%)	Hedges' g* (95% CI)	
		HGS	GS
≤ 4.25°	34 (39.1)	-0.61 (-1.04 – -0.17)	-0.68 (-1.12 – -0.24)
≤ 4.54°	49 (56.3)	-0.7 (-1.13 – -0.26)	-0.49 (-0.92 – -0.07)
≤ 5.25°	76 (87.4)	-1.03 (-1.67 – -0.38)	-0.17 (-0.8 – 0.46)

**Hedges' g compares low versus normal phase angle groups; negative values indicate lower performance in the low phase angle groupHGS: Handgrip strength, GS: Gait speed.*

Table 3. Effect sizes of handgrip strength and gait speed across phase angle cut-offs.

	SQSM- Operationalised definition of sarcopenia (PhA ≤ 4.25°)	AWGS defined sarcopenia
Prevalence	30 (34.5%)	4 (4.6%)
Cohen's Kappa	0.104	-
McNemar's χ^2	22.32	-
McNemar p-value	<0.001	-
Falls (adjusted OR (95% CI))	5.77 (1.64-23.04)	25.64 (1.60-806.80)
P value	0.008[b]	0.029[b]

Adjusted for age group, sex and BMI. OR = Odds ratio; CI = Confidence Interval. [b]: p<0.05 using logistic regression.

Table 4. Prevalence, Agreement, and Fall Risk Associated with SQSM (PhA ≤ 4.25°) and AWGS 2019 Sarcopenia Definitions (n = 87).

p = 0.904, respectively).

Regarding falls, a significant association was only observed with the ≤4.25° cutoff (OR = 4.20; 95% CI: 1.25–15.7; *p* = 0.024), while higher cutoffs showed no significant relationship.

The cutoff of phase angle ≤ 4.25° was derived from ROC analysis conducted within this study population to identify individuals with low ASM/height^2. The ROC curve demonstrated moderate discriminatory ability, with an area under the curve (AUC) of 0.712. The optimal cutoff was determined based on the Youden Index (0.475), which yielded a sensitivity of 83.3% and specificity of 64.2%. In comparison, alternative cutoffs derived from external studies were also assessed. Both the ≤ 4.25° and ≤ 4.54° cutoffs had identical sensitivity (83.3%) for detecting low ASM/height^2, though specificity was lower for the latter (45.7%). The higher cutoff of ≤ 5.25° achieved perfect sensitivity (100.0%) but demonstrated poor specificity (13.6%).

Table 3 illustrates the effect sizes across different phase angle cut off values against hand grip strength and gait speed. Lower phase angle is strongly associated with weaker hand grip strength across all cut off values. In contrast, the association for gait speed is low at higher cut off values, suggesting that hand grip strength is more sensitive discriminator for this study cohort.

Comparison Between SQSM and AWGS 2019 Sarcopenia Definitions and Their Association with Falls

Table 4. compares the prevalence, diagnostic agreement, and fall risk associated with SQSM-OD of sarcopenia (PhA ≤ 4.25°) and AWGS 2019-defined sarcopenia. The prevalence of sarcopenia was substantially higher when defined by SQSM (34.5%) compared to AWGS criteria (4.6%). Agreement between the two definitions was low, with a Cohen's Kappa of 0.104, and McNemar's test indicated significant disagreement in classification (χ^2 = 22.32, p < 0.001).

In multivariate logistic regression adjusted for age group, sex, and BMI, SQSM-OD of sarcopenia was significantly associated with increased odds of falls (adjusted OR = 5.77, 95% CI: 1.64–23.04, p = 0.008). Similarly, AWGS-

defined sarcopenia was also significantly associated with falls (adjusted OR = 25.64, 95% CI: 1.60–806.80, p = 0.029), although the wide confidence interval reflects the low number of AWGS-classified cases.

Discussion

Phase Angle as a Marker of Muscle Quality

This study investigated the utility of phase angle as a clinical marker for sarcopenia within the SQSM framework and its potential to complement current sarcopenia definitions. Phase angle reflects the electrical integrity across the muscle cell membrane, with higher values reflective of higher muscle performance[14]. The strong linear relationship between phase angle and hand grip observed at higher phase angle thresholds is consistent with this rationale, as hand grip strength is measured using a single maximal isometric contraction. In contrast, studies have suggested that the gait speed involves more complex systems such as balance, joint health and cardiovascular health, rather than a pure proxy for muscle health[16]. The divergence of effect size in our study for hand grip strength and gait speed echoes this perspective. Therefore, while both hand grip strength and gait speed are widely utilised tools of functional measures, they should not be interchangeable and appear to capture distinct aspects of physical function.

Our findings suggest that PhA is a multidimensional marker of muscle function with specific thresholds of functional decline. We identified a PhA cut-off of 4.54° as predictive of low muscle strength, while a lower threshold of 4.25° identified individuals with slow gait speed and a history of falls. These results align with previous studies, linking low PhA and impaired muscle function[17-19]. While these values may be cohort specific and require further validation in more diverse populations, the moderate effect size indicates PhA's clinical value as a screening tool, even before significant muscle mass loss occurs. By priortising muscle quality over quantity, PhA aligns with the SQSM framework and offers an objective biomarker for both sarcopenia risk and monitoring progress in resistance-based exercise among older adults[20,21].

Contrary to previous studies, we did not observe a significant sex difference in phase angle values. Although our small sample size limits statistical power, effect size calculations suggest that any true difference is likely minimal in our study cohort. This may be partly explained by the relatively high BMI among female participants in our cohort, which could attenuate sex-based disparities in PhA. Similar trends have been observed in cohorts with higher BMI, where differences in PhA between males and females appeared less pronounced[22].

Towards Bridging Consensus Gaps in Muscle Quality Evaluation

Phase angle identified a greater number of participants with low strength or mobility limitations compared to muscle mass estimate. While appendicular skeletal muscle mass index (ASMI) remains a widely used criterion in sarcopenia diagnosis, it often fails to capture true functional impairment. This discordance was often observed in individuals with normal estimated muscle mass but poor muscle function, a pattern commonly seen in sarcopenia research[23-25]. In our analysis, the lack of agreement between phase angle and ASM/height^2 as evidenced by a non-significant kappa but a significant McNemar test, which suggests these measures may be identifying distinct subgroups of at-risk individuals. This reinforces the notion that muscle mass alone is insufficient to reflect functional decline. Our findings support the conceptual basis of the SQSM framework, which emphasises muscle quality and function as central to sarcopenia identification. Phase angle's ability to detect individuals with strength and mobility limitations and who are at increased risk of adverse outcomes such as falls underscores its added clinical value. Incorporating phase angle into routine assessments may improve early detection of functional vulnerability and enable more targeted interventions to prevent downstream consequences like falls.

Conclusion

Low phase angle demonstrated significant associations with muscle strength, gait speed and falls among older adults supporting its role as a multidimensional marker of muscle function. These findings provide preliminary support for the Structure–Quality–Strength–Mobility (SQSM) model which underscores muscle quality and functional performance over structural measures such as muscle mass estimates. Notably, phase angle identified functional impairments that were not captured by appendicular skeletal muscle mass index alone, highlighting its potential to detect individuals at risk for sarcopenia-related adverse outcomes and could be incorporated into geriatric assessments. While these early findings are promising, the SQSM framework requires validation in larger, more diverse populations. Future studies should also examine longitudinal outcomes to establish its prognostic utility in clinical and community settings.

Limitation

Several limitations should be considered. Firstly, the sample size was relatively small and drawn from a single exercise cohort, which reduces statistical power. To address concerns about data skewness, two participants aged ≥80 years were excluded. The data collection occurred at the

conclusion of a structured exercise program, subjecting to both selection and survivor bias. The cohort likely represents a group with a higher level of functioning and motivation compared to the general population. However, it is important to clarify that this study was designed as a conceptual and exploratory framework to capture multidimensional nature of muscle health within the SQSM model, and therefore informing future research and application. The small data sample size has also resulted in wide confidence intervals in several analyses, reflecting its limited outcome events causing imprecision. To mitigate these, future studies should prioritise larger cohorts with extended follow up to ensure sufficient number of outcomes for more robust validation. Secondly, the cross-sectional design limits the ability to establish causal relationships or assess changes over time. Finally, although cohort-derived cutoffs were used to reflect local characteristics, they may limit generalisability. However, the inclusion of thresholds from external studies enhances interpretability and enables comparison with existing literature.

Ethics approval

Ethical approval was obtained from Biomedical Research Ethics Unit [(82/23) KK/JPD/BREU/4/11(a)] and the Medical and Health Research Ethics Committee [Ref: MHREC/MOH/2023/33(1)]. This study was conducted in accordance with the ethical principles of the Declaration of Helsinki of 1964 and its later amendments.

Consent to participate

Written informed consent was obtained from all participants prior to their inclusion in the study.

Authors' contributions

SAR and CWT were involved in the conception, design, analysis and interpretation of the data. SAR drafted the initial manuscript. CWT and SPT provided supervision, methodological guidance, and major critical revisions of the manuscript. AH, KHA-M, SH, DRI, SS, and ZZ contributed to participant recruitment and data acquisition. All authors critically reviewed the manuscript, contributed intellectual input, and approved the final version.

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References

1. Fielding RA, Vellas B, Evans WJ, Bhasin S, Morley JE, Newman AB, et al. Sarcopenia: an undiagnosed condition in older adults. J Am Med Dir Assoc. 2011;12(4):249–56.
2. Pahor M, Manini T, Cesari M. Sarcopenia: clinical evaluation, biological markers and other evaluation tools. J Nutr Health Aging. 2009 Oct;13(8):724–8.
3. Evans WJ, Cawthon PM. D3-creatine dilution as a direct, non-invasive and accurate measurement of muscle mass for aging research. Calcif Tissue Int. 2024;114(1):3–8.
4. Prado CM, Heymsfield SB. Lean tissue imaging: a new era for nutritional assessment and intervention. JPEN J Parenter Enteral Nutr. 2014 Nov;38(8):940–53.
5. Schaap LA, Koster A, Visser M. Adiposity, muscle mass, and muscle strength in relation to functional decline in older persons. Epidemiol Rev. 2013;35(1):51–65.
6. Newman AB, Kupelian V, Visser M, Simonsick EM, Goodpaster BH, Kritchevsky SB, et al. Strength, but not muscle mass, is associated with mortality in the Health, Aging and Body Composition Study cohort. J Gerontol A Biol Sci Med Sci. 2006;61(1):72–7.
7. Harvey NC, Kanis JA, Liu E, Cooper C, Lorentzon M, Bea JW, et al. Predictive value of DXA appendicular lean mass for incident fractures, falls, and mortality, independent of prior falls, FRAX, and BMD: Findings from the Women's Health Initiative (WHI). J Bone Miner Res. 2021;36(4):654–61.
8. Cruz-Jentoft AJ, Bahat G, Bauer J, Boirie Y, Bruyère O, Cederholm T, et al. Sarcopenia: revised European consensus on definition and diagnosis. Age Ageing. 2019;48(1):16–31.
9. Bhasin S, Travison TG, Manini TM, Clark RV, Cawthon PM, Pencina KM, et al. Sarcopenia definition: the position statements of the Sarcopenia Definition and Outcomes Consortium. J Am Geriatr Soc. 2020;68(7):1410–8.
10. Woo J, Cruz-Jentoft AJ, Lee JSW, Arai H, Reginster JY, Morley JE, et al. The conceptual definition of sarcopenia: Delphi consensus from the Global Leadership Initiative in Sarcopenia (GLIS). J Cachexia Sarcopenia Muscle. 2024;15(2):345–56.
11. Cruz-Jentoft AJ, Bahat G, Bauer J, Boirie Y, Bruyère O, Cederholm T, et al. Sarcopenia: revised European consensus on definition and diagnosis. Age Ageing. 2019;48(1):16–31.
12. Chen LK, Woo J, Assantachai P, Auyeung TW, Chou M-Y, Iijima K, et al. Asian Working Group for Sarcopenia: 2019 Consensus Update on Sarcopenia Diagnosis and Treatment. J Am Med Dir Assoc. 2020;21(3):300–7.e2.
13. Correa-de-Araujo R, Harris-Love MO, Miljkovic I, Fragala MS, Manini TM. Muscle quality: integrating structural and functional considerations in skeletal muscle evaluation. Front Physiol. 2017;8:87.
14. Norman K, Stobäus N, Pirlich M, Bosy-Westphal A. Bioelectrical phase angle and impedance vector analysis – clinical relevance and applicability of impedance parameters. Clin Nutr. 2012;31(6):854–61.
15. Zhang J, Wang N, et al. The diagnostic accuracy and cutoff value of phase angle for screening sarcopenia: a systematic review and meta-analysis. J Am Med Dir Assoc. 2024.
16. Hyeon G, Kim C, Shin S. The reciprocal relationship between gait and handgrip strength across different age groups. Front Public Health. 2025;13:1557834.
17. Di Vincenzo A, Marra M, Di Gregorio A, Pasanisi F, Scalfi L. Bioelectrical impedance analysis–derived phase angle in

sarcopenia: A systematic review. Clin Nutr. 2021;40(5):3052–61.
18. Kim B, Youm C, Park H, Lee M, Choi H. Association of muscle mass, muscle strength, and muscle function with gait ability assessed using inertial measurement unit sensors in older women. Int J Environ Res Public Health. 2022;19(16):9901.
19. Yamanaka A, Yasui-Yamada S, Furumoto T, Kubo M, Hayashi H, Kitao M, et al. Association of phase angle with muscle function and prognosis in patients with head and neck cancer undergoing chemoradiotherapy. Nutr. 2022 Nov–Dec;103–104:111798.
20. Liu S, Zhang S, Cheng X, Wu D, Chen J, Liang W, et al. A meta-analysis on the impact of resistance training on phase angle in middle-aged and older individuals. Arch Gerontol Geriatr. 2024;119:105318.
21. Borde R, Hortobágyi T, Granacher U. Dose-response relationships of resistance training in healthy old adults: a systematic review and meta-analysis. Sports Med. 2015;45(12):1693–720.
22. Bosy-Westphal A, Danielzik S, Dörhöfer RP, Later W, Wiese S, Müller MJ. Phase angle from bioelectrical impedance analysis: population reference values by age, sex, and body mass index. JPEN J Parenter Enteral Nutr. 2006;30(4):309–316.
23. Newman AB, Kupelian V, Visser M, Simonsick EM, Goodpaster BH, Kritchevsky SB, Tylavsky FA, Rubin SM, Harris TB. Strength, but not muscle mass, is associated with mortality in the Health, Aging and Body Composition Study cohort. J Gerontol A Biol Sci Med Sci. 2006;61(1):72–77.
24. Kim M, Won CW. Muscle strength and physical performance are associated with multimorbidity rather than muscle mass in older adults aged ≥ 70 years. Arch Gerontol Geriatr. 2022;98:104557.
25. Li Y, Wang J, Zhang Z, et al. Associations of Muscle Mass and Strength with All-Cause Mortality among US Older Adults. J Cachexia Sarcopenia Muscle. 2018;9(1):164–170.