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DISERTAČNÍ PRÁCE

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Efekt tance a bojového umění na parametry sarkopenie u starších žen nad 65 let

The effect of dance and martial arts on sarcopenia parameters in older females aged 65 years and over

Vedoucí disertační práce

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Poděkování

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Abstrakt

Souvislosti: Sarkopenie, charakterizovaná progresivním poklesem svalové hmoty, síly a funkce, představuje rostoucí problém u stárnoucích populací, zejména u starších žen, které jsou neúměrně postiženy v důsledku hormonálních změn, nižších základních svalových rezerv a prodloužené délky života. Navzdory tomu současné diagnostické přístupy a cvičební intervence často zdůrazňují maximální svalovou sílu a často zanedbávají kritické aspekty, jako je svalová unavitelnost a faktory kvality svalů, které úzce souvisejí s reálným funkčním poklesem. V reakci na tato omezení si somatické intervence, jako je tanec a bojová umění, získaly pozornost jako vícerozměrné strategie, které nejen zlepšují fyzické funkce, ale také podporují kognitivní, emocionální a sociální pohodu.

Cíle: Cílem této studie bylo vyhodnotit účinky dvou somatických intervencí – tance a bojových umění – na svalovou morfologii, funkci a složení těla u starších žen. Ultrazvuk sloužil jako primární nástroj pro posouzení kvality svalů a rizika sarkopenie. Další důraz byl kladen na měření svalové unavitelnosti jako dalšího parametru souvisejícího se sarkopenií. Sekundárním cílem bylo prozkoumat korelace mezi klíčovými parametry souvisejícími se sarkopenií prostřednictvím průřezové analýzy s cílem identifikovat praktické, neinvazivní indikátory svalové funkce.

Metody: Kohorta 64 starších žen se účastnila buď taneční skupiny (DG), skupiny bojových umění (MaG), nebo kontrolní skupiny (CG) po dobu 12 týdnů. Před intervencí a po ní byly hodnoceny ukazatele svalové morfologie - echo intenzita (EI), tloušťka svalu (MT), úhel pennace (PA) a délka svalových vláken (FL), složení těla – body mass index (BMI), % tuku, hmotnost a index kosterního svalstva a svalové funkce - maximální isometrická volní kontrakce (MVC), síla stisku ruky (HG), rychlost chůze, vstávání ze židle a index únavy. Ultrazvukový index sarkopenie (USI) byl vypočítán jako poměr FL a MT. Každá intervence byla posouzena nezávisle oproti kontrolní skupině bez přímého srovnání mezi typy intervencí. Byla provedena sekundární průřezová analýza za účelem identifikace korelací mezi svalovou morfologií, složením těla a ukazateli svalové funkce s cílem prozkoumat vztahy prediktorů svalové funkce.

Výsledky: DG a MaG vykazovaly statisticky významný nárůst PA o 5 % a 6,7 % ($p < 0,05$), respektivě. MaG navíc prokázal významný 8% nárůst MT a 4,5% nárůst FL ($p < 0,05$). Dále byly pozorovány významné změny v EI s rozdílem změny -3,51 pro DG a -2,94 pro MaG, stejně jako v USI pro MaG (-0,14) ve srovnání s CG ($p < 0,05$). Je zajímavé, že CG zaznamenala významný pokles PA, MT a FL ($p < 0,05$). Nebylo zjištěno žádné významné zlepšení složení těla před zahájením intervence napříč skupinami. MaG však vykazovala významné negativní změny v BMI, SMM a SMI ve srovnání s CG ($p < 0,05$). Nakonec, pouze MaG vykazovala zlepšení indexu únavy, ačkoli toto zlepšení nebylo ve srovnání s CG významné. Průřezová analýza odhalila silné významné nové souvislosti mezi morfologickými a výkonnostními proměnnými, jako například mezi MVC a indexem únavy, EI a USI, nebo mezi procentem tuku a EI ($p < 0,05$).

Závěry: Ačkoli celkové změny naměřených parametrů souvisejících se sarkopenií byly mírné, účastníci bojových umění vykazovali konzistentnější zlepšení svalové architektury a indexu únavy. Zdá se, že oba holistické intervenční přístupy dohromady slouží jako preventivní opatření proti sarkopenii související s věkem u starších žen. Začlenění hodnocení svalové únavy a ultrazvukového vyšetření do běžné praxe by mohlo zlepšit včasnou detekci a personalizovanou léčbu sarkopenie. Průřezová analýza dále potvrdila silnou souvislost mezi morfologickými a výkonnostními proměnnými. Konkrétně tato studie zjistila, že kvalita svalů měřená EI a síla horních končetin jsou u starší ženské populace robustnějšími prediktory síly dolních končetin než samotný věk.

Klíčová slova: stárnutí, sarkopenie, pohybová intervence, tanec, bojová umění, kvalita svalů, svalová únava, ultrazvukové zobrazování

Abstract

Background: Sarcopenia, defined by the progressive decline in muscle mass, strength, and function, presents an increasing challenge within ageing populations. This issue is particularly pronounced among older women, who are disproportionately affected due to hormonal changes, lower baseline muscle reserves, and increased longevity. Despite this, prevailing diagnostic methods and exercise interventions often prioritize maximal muscle strength, frequently overlooking critical factors such as muscle fatigability and muscle quality, which are closely associated with real-world functional decline. In response to these limitations, somatic-based interventions, including dance and martial arts, have garnered attention as multidimensional strategies that not only enhance physical function but also support cognitive, emotional, and social well-being.

Objectives: This study aimed to evaluate the effects of two somatic-based interventions—dance and martial arts—on muscle morphology, function, and body composition in older women. Ultrasound was employed as the primary tool for assessing muscle morphology and sarcopenia risk. Additional emphasis was placed on measuring muscle fatigability as another parameter related to sarcopenia. A secondary objective was to explore correlations among key sarcopenia-related parameters through cross-sectional analysis to identify practical, non-invasive indicators of muscle function.

Methods: A cohort of 64 older women was assigned to either a dance group (DG), a martial arts group (MaG), or a control group (CG) for a duration of 12 weeks. Pre- and post-intervention assessments included ultrasound-derived indicators of muscle morphology in the vastus lateralis muscle, specifically echo intensity (EI), muscle thickness (MT), pennation angle (PA), and fiber length (FL). Additionally, body composition metrics such as body mass index (BMI), fat percentage, skeletal muscle mass, and skeletal muscle index were evaluated, alongside measures of muscle function, including maximal voluntary isometric contraction (MVC), handgrip strength (HG), gait speed, chair stand performance, and fatigability index. The ultrasound sarcopenia index (USI) was calculated as the ratio of fiber length (FL) to muscle thickness (MT). Each intervention was independently compared to the control group, without direct comparisons between the intervention types. A secondary cross-sectional analysis was conducted to identify correlations between muscle morphology, body composition, and muscle function measures, with the objective to identify predictors of muscle function.

Results: DG and MaG exhibited statistically significant increases in PA of 5% and 6.7%, respectively (p < 0.05). Additionally, MaG demonstrated a significant 8% increase in MT and a 4.5% increase in FL ($p < 0.05$). Furthermore, significant changes were observed in EI, with a change difference of -3.51 for DG and -2.94 for MaG, as well as in USI for MaG (-0.14) , when compared to the CG ($p < 0.05$). Interestingly, the CG experienced significant decreases in PA, MT, and FL ($p < 0.05$). No significant pre-post improvements in body composition were detected across the groups. However, MaG showed significant negative changes in BMI, SMM, and SMI compared to CG ($p < 0.05$). Finally, only MaG exhibited pre-post improvement in fatigability, although this was not significant compared to CG. Cross-sectional analysis revealed strong significant novel associations between morphological and performance variables, such as between MVC and the fatigability index, EI and USI, or between fat percentage and EI ($p < 0.05$).

Conclusion: Although the overall changes in measured parameters related to sarcopenia were modest, participants in martial arts exhibited more consistent improvements in muscle architecture and fatigability. Collectively, both holistic intervention approaches appear to serve as preventive measures against age-related sarcopenia in older women. The incorporation of muscle fatigability and ultrasound-based assessments into routine practice could enhance early detection and personalized management of sarcopenia. Furthermore, cross-sectional analysis confirmed strong associations between morphological and performance variables. Specifically, this study identified that muscle quality measured by EI and upper-limb strength are more robust predictors of lower-limb strength than age alone in the older female population.

Key words: ageing, sarcopenia, exercise intervention, dance, martial arts, muscle quality, fatigability, ultrasound imaging

Seznam použitých zkratek

ASM	Appendicular Skeletal Muscle Mass
AT	Aerobic Exercise Training
AUFC	Area Under the Force Versus Time Curve
AWGS	Asian Working Group for Sarcopenia
BIA	Bioelectrical Impedance Analysis
BMI	Body Mass Index
CG	Control Group
CSA	Cross-Sectional Area
DG	Dance Group
DXA	Dual-Energy X-Ray Absorptiometry
EI	Echo Intensity
EMG	Electromyography
EWGSOP	European Working Group on Sarcopenia In Older People
FATI3	Fatigue Index Protocol 3
FL	Fibre Length
FNIH	Foundation for The National Institutes of Health
Glms	Generalised Linear Models
GS	Gait Speed
HG	Hand Grip Strength
Hsmi	Height-Adjusted Skeletal Muscle Index
ICC	Intraclass Correlation Coefficient
IGF-1	Insulin-Like Growth Factor-1

IL	Interleukin
IWGS	International Working Group on Sarcopenia
LMA	Laban Movement Analysis
Mag	Martial Arts Group
MT	Muscle Thickness
MVC	Maximal Isometric Voluntary Contraction
NMJ	Neuromuscular Junction
PA	Pennation Angle
Qol	Quality of Life
ROS	Reactive Oxygen Species
RT	Resistance Training
SD	Standard Deviation
SMI	Skeletal Muscle Index
SMM	Skeletal Muscle Mass
SPPB	Short Physical Performance Battery
TNF	Tumour Necrosis Factor
TPM	Time Point of Maximum
TUG	Timed Up-And-Go
USI	Ultrasound Sarcopenia Index
VL	Vastus Lateralis

Obsah

1 General introduction

It is well-established that the ageing process presents significant medical and socioeconomic challenges associated with numerous age-related non-communicable diseases (Monaco et al., 2020; Prince et al., 2015). These conditions have a profound impact on quality of life (QoL) and functional independence, with around 50% of individuals aged 65 and older in Europe reporting challenges with at least one personal care or household activity (Eurostat, 2022). Sarcopenia, characterised by the progressive loss of skeletal muscle mass and function, is a significant health concern among older adults. Moreover, sarcopenia is often accompanied by myosteatosis, the infiltration of adipose and connective tissue into muscles, which diminishes muscle quality and impairs functional performance in older adults (Delmonico et al., 2009). This age-related condition not only impacts physical strength and mobility but also profoundly affects an individual's quality of life (QoL) and ability to maintain independence in daily activities (Cruz-Jentoft et al., 2019; Moore et al., 2014). While prevalence estimates vary across studies and healthcare settings, research indicates that rates range from approximately 8% to 40% globally in older adults aged 60 years and over, with a higher incidence observed in advanced age groups (Petermann-Rocha et al., 2022). As the global population continues to age, the prevalence of sarcopenia is expected to rise, making it one of the most common non-communicable diseases associated with advancing years.

The complexity of sarcopenia's origins extends beyond simple age-related factors, encompassing a multifaceted interplay of physiological, lifestyle, and environmental elements. While reduced physical activity is a significant contributor, other factors such as hormonal changes, chronic inflammation, mitochondrial dysfunction, and alterations in protein synthesis and breakdown also play crucial roles (Nishikawa et al., 2021). The intricate relationship between these factors makes it challenging to pinpoint a single primary cause, leading to ongoing debates within the scientific community about the relative importance of intrinsic ageing processes versus external influences, such as sedentary behaviour.

While this condition impacts both genders, emerging evidence suggests that women may face a more challenging prognosis (Petroni et al., 2019). This gender disparity can be attributed to several factors, including hormonal changes during menopause, differences in muscle composition, and variations in physical activity patterns between men and women as they age (Lee, 2005). The potentially worse prognosis for women with sarcopenia has important implications for healthcare and public health strategies. Women tend to have lower muscle mass and strength compared to men throughout their lives, which may accelerate the progression of sarcopenia and its associated complications. Additionally, the decline in estrogen levels during menopause can further exacerbate muscle loss and functional decline (Cho et al., 2022; Lu & Tian, 2023). These factors contribute to an increased risk of falls, fractures, and loss of independence among older women with sarcopenia, highlighting the need for targeted interventions and early detection strategies specifically tailored to address the unique challenges faced by this demographic.

Sarcopenia has emerged as a critical concern in ageing populations, yet its diagnosis remains fraught with inconsistency and inaccessibility, particularly for older women. Current diagnostic criteria prioritise measurements of muscle mass, strength, and function, typically relying on dual-energy X-ray absorptiometry (DXA), handgrip strength (HG), and gait speed (Cruz-Jentoft et al., 2019; Chen et al., 2020). While HG and gait speed are feasible in most clinical settings, DXA is costly, requires specialised personnel, and is often unavailable outside major medical centers. For this reason, bioelectrical impedance analysis (BIA) has been proposed as a practical alternative due to its portability, affordability, and ease of use. However, its accuracy is compromised in populations where fluid and body composition distribution may be altered, such as in older individuals (Csiernik et al., 2022). In fact, the current body of evidence does not consistently support the use of BIA as a reliable diagnostic tool for sarcopenia in adults over 60 years of age (Csiernik et al., 2022). Additionally, gender-specific differences in fat distribution and hydration status may further reduce the accuracy of BIA, which is particularly concerning for older women.

For the above-mentioned reasons, ultrasound imaging represents a promising yet underutilized alternative for the assessment of sarcopenia, particularly in older female populations. It is portable, non-invasive, cost-effective, and increasingly validated as a reliable method for evaluating both muscle quantity and quality in clinical and research settings (Prell et al., 2024; Stringer & Wilson, 2018). Traditional ultrasound techniques enable the assessment of several muscle morphology parameters, including muscle thickness (MT), cross-sectional area (CSA), pennation angle (PA), fascicle length (FL), and echo intensity (EI)) (Pillen & van Alfen, 2011; Pillen et al., 2009). Among these, EI is especially relevant, as it provides an estimate of intramuscular fat and fibrous tissue infiltration by analysing grayscale pixel intensity within a defined region of interest (Stock & Thompson, 2021). This marker has shown strong correlations with muscle strength and physical performance in older adults (Rech et al., 2014; Yuan & Kim, 2023), highlighting its utility in detecting qualitative muscle degradation that may not be apparent through size-based measurements alone.

Additionally, the recently proposed Ultrasound Sarcopenia Index (USI), which is based on the geometric proportions of muscle architecture, offers a novel and potentially powerful tool for identifying sarcopenia in older populations (Narici et al., 2021). The versatility of ultrasound in detecting sarcopenia extends beyond controlled laboratory environments, making it particularly useful for large-scale community assessments. Notably, the reliability of ultrasound measurements remains consistent across different demographic groups, regardless of gender, allowing for standardised evaluations (Minetto et al., 2016; Yang et al., 2025). This capability enables healthcare professionals to identify individuals at risk of sarcopenia earlier in the disease progression, potentially leading to more timely interventions and improved outcomes for patients. Its integration into standard diagnostic pathways could help close the gap in sarcopenia detection, particularly among older women, who are too often underdiagnosed and underserved.

To date, most research on sarcopenia has focused on muscle strength, either as a measured variable or as the primary target of exercise interventions (Lu et al., 2021; Peterson et al., 2010). While muscle strength is undeniably a crucial aspect of physical function, it represents only one facet of the broader capabilities required for independent living and (QoL) in older age. This is particularly relevant for older females, who often experience greater declines in physical function compared to their male counterparts and typically live longer (ref.), thereby increasing their risk of prolonged periods of functional limitation. Many daily activities performed by older women—such as carrying groceries, climbing stairs, or completing household chores—involve sustained, submaximal effort rather than brief, maximal exertion (Hortobagyi et al., 2003). These tasks require endurance and fatigue resistance, which may be more indicative of functional capacity and (QoL) than strength alone. Therefore, there is a growing need to shift the research focus toward endurance and fatigue resistance, especially in older females, as these factors may better reflect the physical demands of their daily lives and have greater implications for maintaining independence and well-being.

The impact of exercise on sarcopenia prevention and management is multifaceted, extending beyond the preservation of muscle mass and strength. Regular physical activity has been shown to modulate various biological pathways implicated in sarcopenia, including improved insulin sensitivity, reduced oxidative stress, and enhanced neuromuscular function

(Lim & Kang, 2023; Sanchez-Sanchez et al., 2024). Moreover, the benefits of exercise in maintaining muscle health have far-reaching implications for overall well-being, contributing to improved metabolic health, bone density, cognitive function, and psychological well-being (Falck et al., 2019). This holistic approach to health through muscle maintenance emphasises the importance of integrating exercise interventions into strategies that promote healthy ageing and enhance quality of life across the lifespan. For older adults, particularly older women, social isolation has become a pressing concern, as it can significantly impact both physical and mental health (Donovan & Blazer, 2020). In this demographic, isolation often leads to a reduction in physical activity, which can, in turn, exacerbate declines in muscle function, contribute to frailty, and diminish overall QoL. Given the unique challenges faced by older women, such as hormonal changes, a greater risk of sarcopenia, and a higher likelihood of living alone, interventions that promote both physical and emotional well-being are essential.

Dance and martial arts, two somatic-based practices, have shown promise as effective interventions for older adults, offering benefits that extend beyond the physical. These activities can help foster social interaction, improve mental health, and enhance body awareness—all crucial elements for older women who may be at higher risk of social isolation. Dance, for instance, is a multifaceted activity that combines aerobic exercise with emotional expression and social engagement, which can significantly improve muscle strength, balance, and coordination (Liu et al., 2021). Similarly, martial arts offer a unique combination of strength training, balance, and mental focus, providing a way to challenge both the body and mind, which may be particularly beneficial for combating the cognitive and physical decline that accompanies ageing (Linhares et al., 2023). Both interventions are especially well-suited for older women, as they help counteract the physical effects of ageing, such as muscle loss, while also addressing the emotional and social aspects of ageing that are often overlooked.

2 Study aims

The brief general introduction has outlined several key gaps and limitations in the current understanding of sarcopenia, particularly regarding its assessment, gender-specific implications, and the narrow focus on maximal muscle strength as a primary indicator of functional health in older adults. These limitations are especially critical in the context of older women, who face a higher risk of sarcopenia due to hormonal changes, lower muscle reserves, and increased longevity. Moreover, commonly used diagnostic tools may overlook important aspects of muscle quality and fatigability, which are central to everyday functioning.

Given these gaps, the rationale for the present study was to adopt a more comprehensive and ecologically valid approach to evaluating and addressing sarcopenia in older women. By examining the effects of two somatic-based interventions - dance and martial arts—on a broad spectrum of sarcopenia-related parameters, including ultrasound-derived muscle morphology (integrating the use of EI and USI), muscle strength and function (including fatigability), and body composition, this research aimed to provide a more nuanced, non-invasive, and accessible method for assessing skeletal muscle health. However, this study did not aim to compare the two intervention modalities against each other. Instead, each was evaluated independently compared to a non-intervention control group to examine their specific effects on selected outcome measures.

Furthermore, through secondary cross-sectional analysis, the study explored correlations between the measured parameters to identify potential practical predictors of muscle decline, thereby contributing to early detection and the development of individualised intervention strategies.

Primary Aim (Intervention):

To assess the effects of two somatic-based practices - dance and martial arts on sarcopenia-related parameters in older women, including muscle morphology (integrating EI), muscle function (including the measure of fatigability), and body composition.

Secondary Aim (Cross-Sectional Analysis):

To explore associations between all measured parameters, regression models were used to identify predictors of muscle strenght and performance.

2.1 Research questions

Intervention-related:

1. Do dance and martial arts interventions lead to improvements in sarcopenia-related parameters, including muscle morphology, muscle function and body composition in healthy older women?

Cross-sectional (correlational)-related:

2. What are the relationships between measured parameters of muscle morphology, muscle function, and body composition across the female cohort?

3. Is the EI a significant predictor of lower extremities muscle strength and fatigability?

2.2 Study hypotheses

H1 (Intervention):

Participation in the dance or martial arts intervention will significantly improve sarcopenia-related parameters compared to the baseline and control groups.

H2 (Cross-sectional):

Muscle morphology parametres will be positively associated with muscle strength and negatively associated with fatigability.

H3 (Cross-sectional):

Regression analysis will reveal that age and EI are significant predictors of muscle quality and function.

3 Theoretical framework

3.1 Definition of sarcopenia

Sarcopenia is an age-related syndrome characterised by a progressive and generalised loss of skeletal muscle mass, strength, and function (Sayer & Cruz-Jentoft, 2022; Shaw et al., 2017). Defined initially solely as the loss of muscle mass with ageing (Rosenberg, 1997), the definition has evolved to incorporate measures of muscle strength and physical performance (Janssen, 2010; Sayer & Cruz-Jentoft, 2022). Research indicates that the rate of muscle mass loss in older adults differs between men and women. According to longitudinal studies, by age 75, women lose muscle mass at a rate of 0.64–0.70% per year, while men experience a slightly higher decline of 0.80–0.98% per year (Mitchell et al., 2012). Muscle strength, on the other hand, declines more rapidly than muscle mass in both sexes. At the same age, men lose 3–4% of their muscle strength annually, and women lose 2.5–3% (Mitchell et al., 2012). This disproportionate loss of strength relative to mass highlights the importance of muscle quality, which is defined by factors such as neuromuscular function, fibre composition, and metabolic efficiency, in assessing age-related functional decline. This shift in perspective acknowledges that the consequences of sarcopenia extend beyond mere quantitative changes in muscle tissue, recognising the functional implications of this condition on an individual's overall health and (QoL).

The official recognition of sarcopenia as a disease by the World Health Organisation in 2016 (Cao & Morley, 2016) and its inclusion in the International Classification of Diseases (ICD-10-CM, M62.84) underscore its clinical importance. This classification distinguishes between primary sarcopenia, which is age-related, and secondary sarcopenia, which results from chronic diseases or reduced mobility. Both forms are prevalent in clinical settings, highlighting the need for healthcare professionals to be vigilant in identifying and addressing sarcopenia in their patients. The consensus focuses on age-related primary sarcopenia, emphasizing the natural progression of muscle loss and functional decline that occurs with advancing age, independent of other health conditions.

To date, four major expert groups have developed widely recognized definitions of sarcopenia, introduced in chronological order:

1. The European Working Group on Sarcopenia in Older People (EWGSOP)

2010 Consensus: The EWGSOP published a consensus definition and diagnostic criteria for sarcopenia, emphasizing the importance of both low muscle mass and low muscle function (strength or performance) for diagnosis (Cruz-Jentoft et al., 2010).

2019 Update (EWGSOP2): An updated definition was released in 2019, emphasising low muscle strength as a key characteristic of sarcopenia and providing revised diagnostic algorithms and cut-off points (Cruz-Jentoft et al., 2019).

2. The International Working Group on Sarcopenia (IWGS)

The IWGS proposed a consensus definition of sarcopenia, highlighting the age-associated loss of skeletal muscle mass and function and recommended specific diagnostic criteria for its identification (Fielding et al., 2011).

3. The Asian Working Group for Sarcopenia (AWGS)

2014 Consensus: The AWGS established a consensus definition for sarcopenia in Asian populations, including specific cut-off points for muscle mass, strength, and physical performance (Chen et al., 2014).

2019 Update: The 2019 update revised diagnostic criteria and introduced the concept of "possible sarcopenia" for earlier detection, along with separate algorithms for community and hospital settings (Chen et al., 2020).

4. The Foundation for the National Institutes of Health (FNIH)

The FNIH Sarcopenia Project proposed a definition of sarcopenia based on appendicular skeletal muscle mass adjusted for body mass index (BMI), handgrip strength, and physical performance measures (Studenski et al., 2014).

While each organization employs slightly different criteria and cut-off thresholds, they all define sarcopenia based on a combination of low skeletal muscle mass, reduced muscle strength (most commonly assessed via handgrip strength), and/or impaired physical performance (typically evaluated through gait speed or chair stand tests). Most guidelines calculate muscle mass as appendicular skeletal muscle mass (ASM) adjusted for height squared, though the FNIH recommends adjusting for body mass index (BMI) instead. A comparative overview of these definitions is provided in **Chyba! Nenalezen zdroj odkazů.Table 1** to illustrate the diagnostic strategies and threshold values used by each group.

Table 1 Operative definitions of sarcopenia according to major expert groups

Consensus Group	Muscle Mass Index	Strength Measure	Physical Performance	Cut-off Examples
EWGSOP (2010; updated 2019)	ASM/height²	Handgrip strength	Gait speed (optional) Chair stand test	ASM: <7.0 kg/m² (men), <5.5 kg/m² (women) HG: <27 kg (men), <16 kg (women) Gait speed: ≤0.8 m/s
IWGS (2011)	ASM/height²	Handgrip strength	Gait speed (mandatory)	Gait speed: ≤1.0 m/s ASM: <7.23 kg/m² (men), <5.67 kg/m² (women)
AWGS (2014; updated 2019)	ASM/height²	Handgrip strength	Gait speed 5-time chair stand / SPPB	HG: <28 kg (men), <18 kg (women) Gait speed: <1.0 m/s
FNIH (2014)	ASM/BMI	Handgrip strength	(Not required)	ASM/BMI: <0.789 (men), <0.512 (women) HG: <26 kg (men), <18 kg (women)

Note: EWGSOP = European Working Group on Sarcopenia in Older People; IWGS = International Working Group on Sarcopenia; AWGS = Asian Working Group for Sarcopenia; FNIH = Foundation for the National Institutes of Health; ASM/ht^2 = ratio of appendicular skeletal muscle mass over height squared; ASM/BMI = ratio of appendicular skeletal muscle mass over body mass index; SPPB = short physical performance battery; HG = handgrip strength

3.2 Prevalence of sarcopenia

A recent systematic review and meta-analysis encompassing 151 studies with over 692,000 participants reported that the global prevalence of sarcopenia ranged from 10% to 27%, depending on the classification and diagnostic criteria used (Petermann-Rocha et al., 2022). However, the prevalence of sarcopenia varies widely across different populations and studies, influenced by factors such as age, gender, health status, and diagnostic criteria used. For example, a study by Reijnierse et al. (2015) compared nine sets of diagnostic criteria and found prevalence rates ranging from 0% to 15% in healthy older participants and 2% to 34% in geriatric outpatients. Another review reported prevalence estimates ranging from 9.9% to 40.4%, depending on the definition used (Mayhew et al., 2019). Moreover, a systematic review of Chinese older adults found prevalence rates of 12.9% in men and 11.2% in women living in communities, with higher rates in hospitals (29.7% in men, 23.0% in women) and nursing homes (26.3% in men, 33.7% in women) (Weng et al., 2025).

In terms of sex differences, a study by Han et al. (2016) found that when using the height-adjusted skeletal muscle index (hSMI), the prevalence of sarcopenia was 6.7% in men and 0.4% in women. However, when using the weight-adjusted skeletal muscle index, the prevalence was 4.0% in men and 10.7% in women. This discrepancy underscores the need for standardised diagnostic criteria for sarcopenia, especially when comparing across genders. Moreover, leveraging current sarcopenia prevalence and demographic trends across 28 EU countries, a study by Ethgen et al. (2017) projects a staggering surge in sarcopenia cases over the next three decades, positioning muscle degeneration as a looming public health crisis (**Figure 1**).

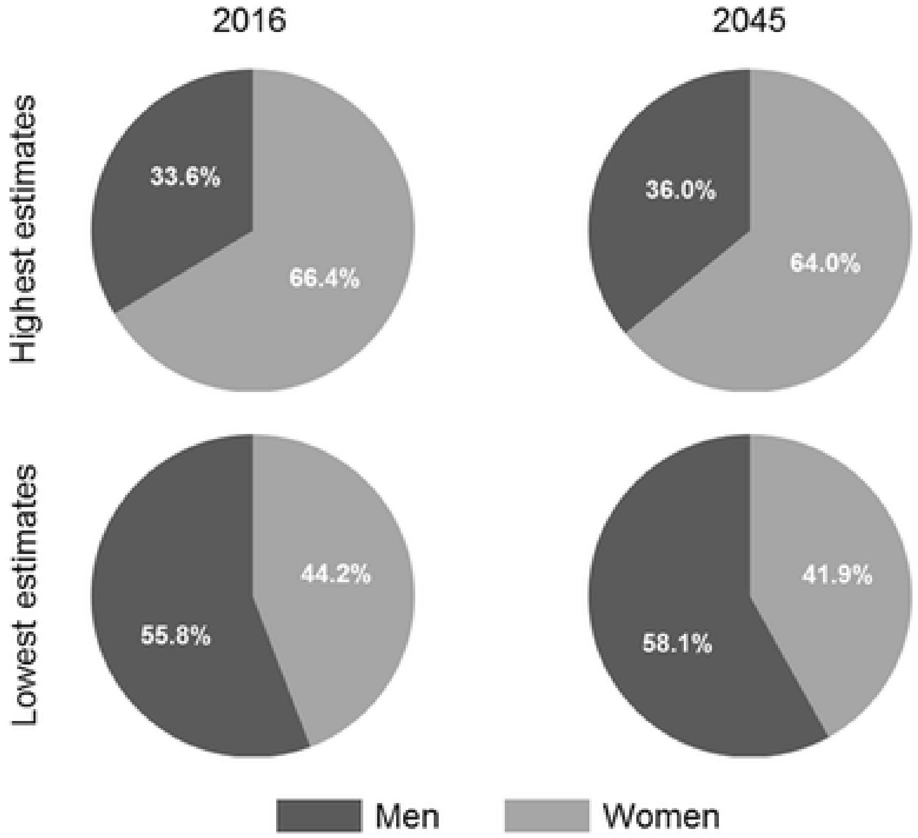

Figure 1 *The projected proportion of men and women affected by sarcopenia between 2016 and 2045 varies depending on the definition used, with estimates presented according to both the highest and lowest diagnostic criteria (taken from Ethgen et al. (2017))*

3.1 Pathophysiology of sarcopenia

The pathophysiology of sarcopenia has been extensively explored in the scientific literature, with numerous studies offering detailed insights into its multifactorial mechanisms (Booth et al., 2012; Collins et al., 2019; Cruz-Jentoft et al., 2019; Ferrucci & Fabbri, 2018; Greising et al., 2009). Given the depth of existing research, this chapter will pinpoint only the most well-established and commonly accepted mechanisms involved in sarcopenia's progression. By focusing on these core mechanisms, the following sections provide a concise yet comprehensive overview of the condition's underlying pathogenesis. While the general principles apply across sexes, particular attention in this discussion will be given to sarcopenia in females, considering the sex-specific physiological, hormonal, and ageing-related differences that may influence muscle degeneration and functional decline in women.

1. Hormonal Decline and Estrogen Deficiency

Age-related hormonal shifts significantly contribute to sarcopenia. Declines in anabolic hormones, including testosterone, growth hormone (GH), and insulin-like growth factor-1 (IGF-1), are commonly observed in elderly populations and are closely linked to reduced muscle mass and function (Morley et al., 2014). In parallel, increased cortisol levels and altered insulin sensitivity exacerbate muscle wasting by favouring catabolism and impairing glucose uptake in muscle tissue. One of the most critical female-specific contributors to sarcopenia is the sharp decline in estrogen levels during menopause. Estrogen plays a crucial role in regulating muscle mass by influencing satellite cell activation, mitochondrial function, and anti-inflammatory signalling (Greising et al., 2009). Estrogen deficiency has been shown to impair muscle regeneration, reduce protein synthesis, and increase oxidative stress, contributing significantly to the onset of sarcopenia in postmenopausal women (Collins et al., 2019).

2. Muscle Protein Turnover and Anabolic Resistance

The core pathophysiological process in sarcopenia involves an imbalance between muscle protein synthesis and muscle protein breakdown. With age, both sexes experience a decline in muscle protein synthesis; however, older women may be more susceptible to "anabolic resistance" - a blunted response to dietary protein and physical activity. This resistance contributes to a net loss in muscle mass over time. Differences in protein metabolism and lower baseline levels of muscle mass in females further exacerbate this imbalance (Wilkinson et al., 2018). Concurrently, catabolic factors such as systemic inflammation and increased myostatin activity promote muscle degradation (Walston, 2012).

3. Neuromuscular Changes

Degenerative changes in the neuromuscular system are another central feature of sarcopenia. Motor neuron loss and the denervation of muscle fibres lead to muscle atrophy, particularly in fast-twitch fibres (Lexell, 1995). The resulting reduction in motor unit number and recruitment efficiency impairs muscle strength and coordination. Although the basic mechanisms are similar across sexes, such as motor neuron loss and muscle fibre denervation, studies suggest that females may experience a different pattern of motor unit remodelling, with slower reinnervation and a greater loss of type II (fast-twitch) fibres (Lexell et al., 1988). This results in reduced power and greater functional decline.

4. Inflammation and Immune Dysregulation

Chronic low-grade inflammation, often referred to as "inflammaging," plays a key role in the pathogenesis of sarcopenia. Elevated levels of pro-inflammatory cytokines such as tumor necrosis factor TNF-α, interleukin IL-6, and CRP are associated with increased muscle protein breakdown and reduced regenerative capacity (Ferrucci & Fabbri, 2018). These cytokines interfere with anabolic signalling and promote insulin resistance, compounding muscle decline. In females, estrogen has been shown to exert anti-inflammatory effects, and its decline may lead to an upregulation of pro-inflammatory cytokines such as IL-6 and TNF-α (Ferrucci & Fabbri, 2018). These cytokines accelerate muscle protein breakdown and interfere with anabolic signalling, compounding muscle deterioration.

5. Mitochondrial Dysfunction and Oxidative Stress

Ageing is associated with a decline in mitochondrial function and an accumulation of reactive oxygen species (ROS), which contribute to muscle cell damage and apoptosis (Short et al., 2005). Oxidative stress impairs mitochondrial biogenesis and disrupts intracellular signalling pathways vital for muscle maintenance. Mitochondrial dysfunction is another shared mechanism of sarcopenia that may present differently in females. Estrogen supports mitochondrial efficiency and antioxidant defences; thus, its decline leads to increased production of reactive oxygen species (ROS), impaired energy metabolism, and muscle apoptosis (Vina et al., 2013). This mechanism is particularly pronounced in postmenopausal women.

6. Physical Inactivity and Lifestyle Factors

Sedentary behaviour accelerates sarcopenia by reducing mechanical loading on muscle, which is essential for maintaining muscle mass and function. Inactivity also leads to reductions in mitochondrial density, insulin sensitivity, and neuromuscular efficiency (Booth et al., 2012). Women, especially in older age, tend to engage in lower levels of resistance-based physical activity compared to men, which further contributes to muscle loss. Sedentary behaviour decreases mechanical loading, leading to reductions in muscle strength, neuromuscular coordination, and metabolic health (Booth et al., 2012).

7. Other contributing factors

Nutritional factors significantly influence sarcopenia in women. Older females often consume insufficient protein and have deficiencies in vitamin D and calcium, which impair muscle protein synthesis and accelerate functional decline (Bauer et al., 2015). Vitamin D, in particular, supports muscle function and calcium regulation. Sarcopenic obesity, marked by fat infiltration into muscle, is more prevalent in ageing women and further compromises muscle quality (Zamboni et al., 2008). Additionally, genetic predispositions may contribute to inter-individual variability in muscle mass and strength, influencing susceptibility to sarcopenia (Delmonico et al., 2007). Comorbidities such as osteoarthritis and cardiovascular disease, both more common in older women, are associated with decreased mobility, increased sedentary behaviour, and poorer muscle function (Abellan van Kan et al., 2009; Bauer et al., 2015; Clynes et al., 2015; Delmonico et al., 2007; Zamboni et al., 2008). **Figure 2** illustrates the most common pathophysiological mechanisms of sarcopenia in females.

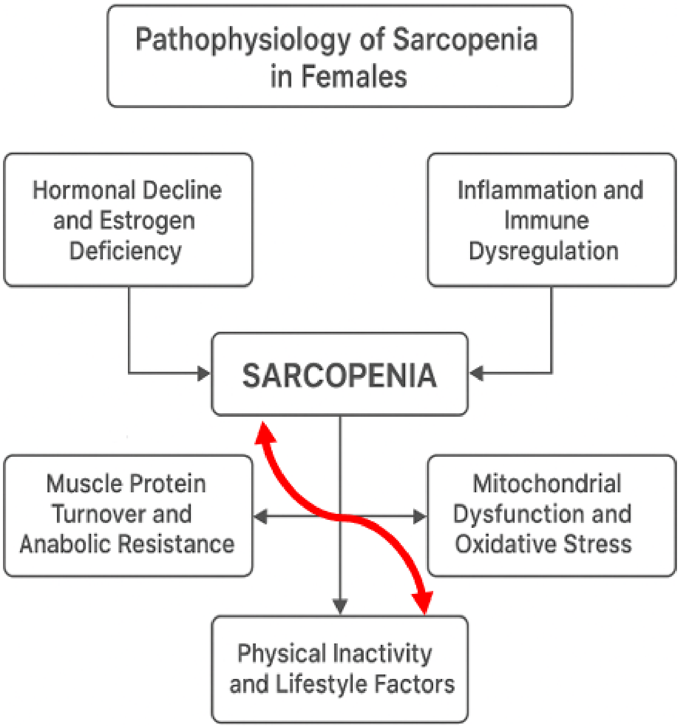

Figure 2 *Pathophysiology of sarcopenia in females*

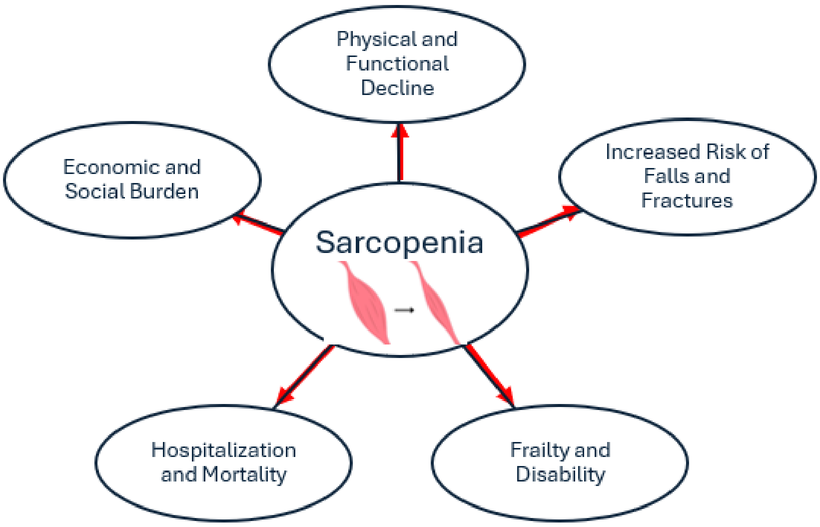

Figure 3 *Consequences of sarcopenia*

3.2 Consequences of sarcopenia

Sarcopenia has far-reaching clinical, functional, and societal consequences, particularly in ageing populations. As muscle mass and strength decline, a cascade of adverse health outcomes can ensue, significantly compromising QoL and increasing healthcare burden. Women are disproportionately affected due to lower baseline muscle mass, hormonal changes, and increased life expectancy. The consequences in females are particularly pronounced, manifesting in physical decline, heightened frailty, and greater risks of disability and dependency.

1. Physical and Functional Decline

One of the primary consequences of sarcopenia is a reduction in physical performance, including decreased gait speed, balance, and overall mobility. These impairments increase the risk of falls and fractures, particularly in older individuals (Beaudart et al., 2017; Collins et al., 2019; Cruz-Jentoft et al., 2019; Fried et al., 2001; Gordon et al., 2017; Landi et al., 2012; Mitchell et al., 2012). Sarcopenic individuals are more likely to experience difficulties with activities of daily living, leading to a loss of independence and increased reliance on caregivers or institutional care (Beaudart et al., 2017).

2. Increased Risk of Falls and Fractures

Sarcopenia is a significant risk factor for falls due to its association with impaired muscle strength and coordination. Falls are a leading cause of injury and mortality in older adults and are often followed by fractures, particularly of the hip, spine, and wrist (Cruz-Jentoft et al., 2010). Estrogen deficiency post-menopause exacerbates both muscle and bone loss, creating a compounded effect that sharply increases fracture susceptibility (Collins et al., 2019). These injuries are not only physically debilitating but are also associated with high rates of morbidity, long-term disability, and even premature death.

3. Frailty and Disability

Sarcopenia contributes significantly to frailty, a clinical syndrome marked by decreased physiological reserve and resilience to stressors (Fried et al., 2001). Frail individuals are more vulnerable to acute illnesses, hospitalizations, and adverse outcomes. Furthermore, sarcopenia is closely linked to chronic disability, leading to progressive decline in both physical and cognitive functions (Morley et al., 2014). The syndrome of frailty is more prevalent in females and is associated with increased vulnerability to stressors, reduced resilience, and greater risk of institutionalization (Fried et al., 2001; Gordon et al., 2017). This leads to higher rates of physical dependence and the need for long-term care among older women.

4. Hospitalization and Mortality

Sarcopenia is associated with increased rates of hospitalisation and longer hospital stays. It is also linked to poorer surgical outcomes, delayed recovery, and increased risk of postoperative complications (Hewitt et al., 2018). Multiple longitudinal studies have established sarcopenia as an independent predictor of all-cause mortality in both community-dwelling and institutionalised older adults (Bianchi et al., 2017). Sarcopenia in women is linked to more extended hospital stays, increased postoperative complications, and delayed recovery, particularly following orthopaedic and abdominal surgeries (Tian et al., 2022). Sarcopenia significantly increases the risk of morbidity and poor clinical outcomes, narrowing the gap between the sexes in terms of long-term survival and recovery (Lera et al., 2021).

5. Economic and Social Burden

The societal costs of sarcopenia are substantial, encompassing both direct healthcare costs and indirect costs from loss of productivity, caregiving needs, and long-term institutionalization. In the European context, the economic burden of sarcopenia is expected to increase significantly due to population ageing (Ethgen et al., 2017). This highlights the importance of early identification and intervention strategies to mitigate long-term public health consequences.

Figure 3 shows the general consequences of sarcopenia.

3.3 Current validated diagnostic tools for sarcopenia parameters

As indicated in Section 3.1, the diagnosis of sarcopenia is currently based on the assessment of diminished muscle mass, muscle strength, and physical performance, utilising a variety of diagnostic tools. In this thesis, we adhere to the validated diagnostic tools recommended by the EWGSOP group (Cruz-Jentoft et al., 2010).

3.3.1 Measurement of muscle mass

As mentioned already in 3.1, the EWGSOP group recommends the use of DXA as the standard method in clinical practice for assessing muscle mass while suggesting BIA as a viable, portable alternative for community or home-based settings (Cruz-Jentoft et al., 2019). DXA is valued for its ability to deliver reproducible and accurate estimates of ASM, particularly when consistent equipment and standardised cut-off values are applied. However, adjustments for body size are necessary to improve the clinical utility of DXA-derived ASM, typically using formulas such as ASM/height^2, ASM/weight, or ASM/BMI (Buckinx et al., 2018; Cruz-Jentoft et al., 2019).

Despite its advantages, DXA has notable limitations, including a lack of portability, sensitivity to hydration status, and the need for standardised adjustment formulas, which limit its application in field studies or widespread community screening (Buckinx et al., 2018). By contrast, BIA is a cost-effective, non-invasive, and radiation-free alternative that is suitable for bedside or home use. However, BIA does not directly measure muscle mass; instead, it estimates it based on whole-body water conductivity using proprietary predictive equations typically validated against DXA (Earthman, 2015). This introduces variability, as outcomes may differ depending on the instrument brand, equation used, and the reference population on which calibration was based (Sergi et al., 2015).

To enhance consistency, EWGSOP recommends reporting raw impedance values in conjunction with validated equations, such as the Sergi equation, which was derived from older European populations and is cross-validated with DXA data (Cruz-Jentoft et al., 2019; Sergi et al., 2015). Nevertheless, caution is warranted. A recent pilot study revealed that BIA tends to overestimate muscle mass in older adults, leading to the misclassification of nearly one in six patients, thus underscoring the need for standardized approaches and confirmatory assessments when using BIA in sarcopenia diagnosis (Reiss et al., 2016). Moreover, the latter study found that sex-specific differences in fat distribution and hydration status may further reduce the accuracy of BIA in this population. As a result, sarcopenia in older females is often underdiagnosed or misclassified, potentially delaying appropriate interventions and accelerating declines in physical function, independence, and overall quality of life. Addressing these diagnostic limitations is essential for ensuring timely and effective management of sarcopenia in this vulnerable group. **Figure 4** shows the current techniques for measuring muscle mass.

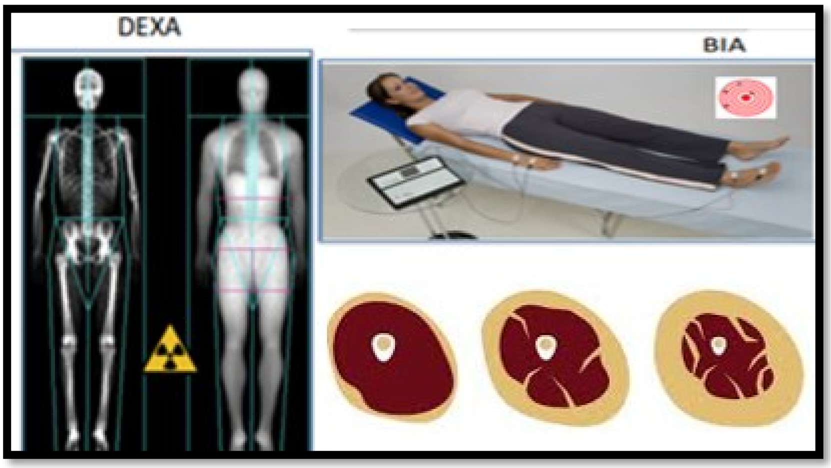

Figure 4 *Current techniques for measuring muscle mass*

3.3.2 Measurement of muscle strength

The EWGSOP, in its most recent revised consensus, recommends the use of isometric handgrip strength (HG) as the primary method for assessing muscle strength in the diagnosis of sarcopenia (Cruz-Jentoft et al., 2019). HG is preferred due to its simplicity, portability, and strong correlation with overall muscular strength and functional outcomes. In cases where HG measurement is not feasible, such as in individuals with upper limb disability, pain, or severe arthritis, the EWGSOP advises the use of isometric torque-based methods to evaluate lower limb strength, such as knee extension strength using a handheld or fixed dynamometer (Cruz-Jentoft et al., 2019; Fragala et al., 2016).

Importantly, the interpretation of muscle strength values should consider individual characteristics, especially stature, which significantly influences absolute strength measures. Therefore, when available, region- and population-specific normative reference values should be applied to improve diagnostic accuracy and minimize the risk of misclassification (Cruz-Jentoft et al., 2019; Dodds et al., 2014). This approach ensures a more accurate identification of sarcopenia across diverse populations, particularly in settings where body size, limb length, or ethnic differences may affect strength measurements.

Sex differences in muscle strength assessment, particularly in the upper and lower limbs, are well-documented and recognised in both clinical practice and research (**Figure 5**). The EWGSOP2 guidelines and related studies acknowledge that men and women differ significantly in absolute muscle strength, and this must be considered during sarcopenia diagnosis (**Figure 6**)

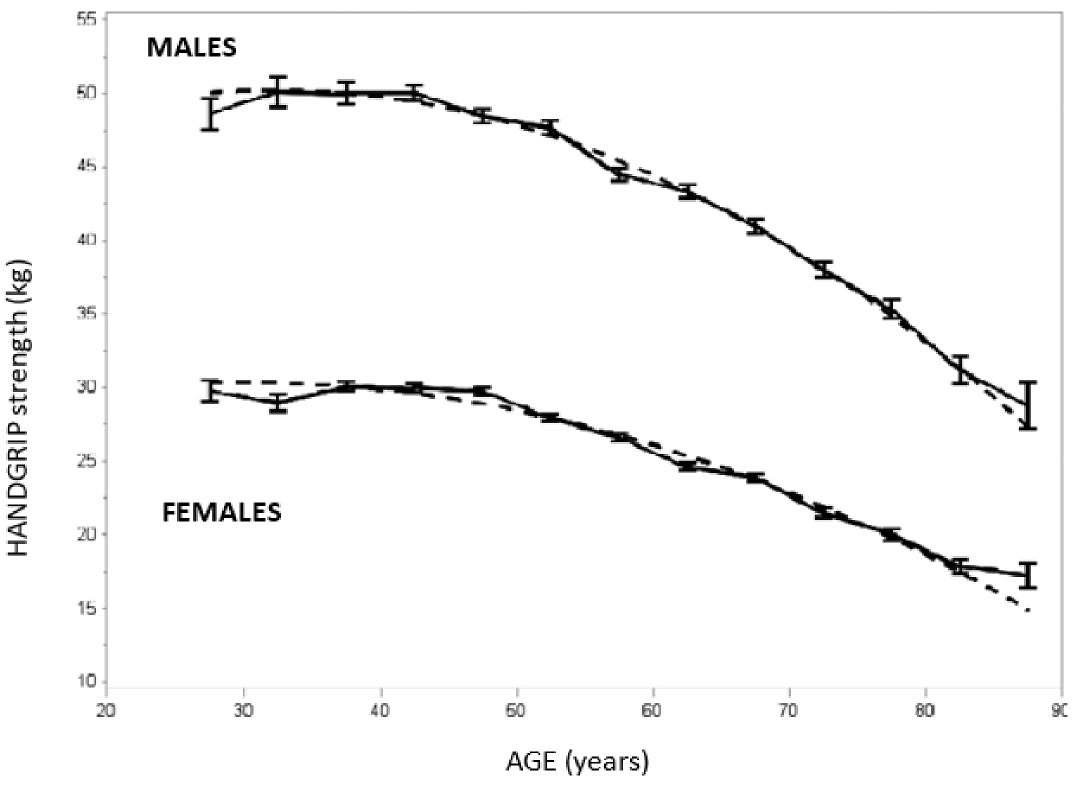

Figure 5 *Handgrip strength (kg) by age groups in men and women (adapted from Murabito et al. (2017))*

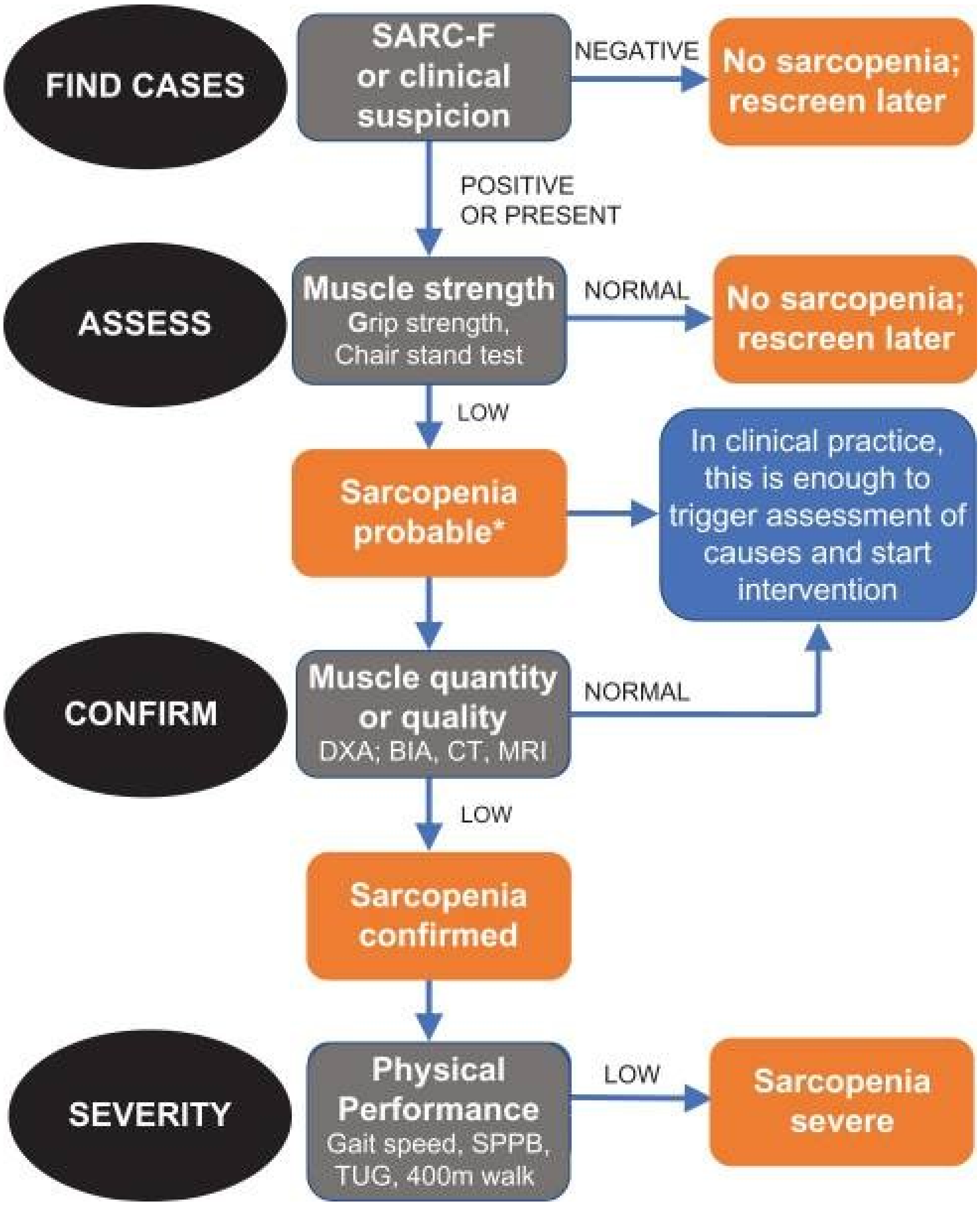

Figure 6 *EWGSOP-suggested algorithm for sarcopenia case finding in older individuals (Cruz-Jentoft et al., 2019).*

3.3.3 Measurement of physical performance

The EWGSOP2 currently recommends the use of the 4-meter gait speed test or the Short Physical Performance Battery (SPPB) (**Figure 7**) for evaluating physical performance due to their strong association with sarcopenia-related outcomes such as falls, functional decline, and mortality and their ease of administration in most settings (Cruz-Jentoft et al., 2019). However, it is important to note that physical performance measures may not be feasible in individuals with certain conditions, such as advanced dementia, balance or gait impairments, or acute illness, where reliable performance cannot be ensured. In such situations, alternative assessments or clinical judgment should be used.

Importantly, sex differences must also be considered when interpreting physical performance results. Older women tend to have slower gait speeds and lower SPPB scores compared to men, even when adjusting for age and health status. This reflects physiological differences such as lower muscle mass, shorter stature, and higher fat mass, as well as greater prevalence of osteoporosis, joint disease, and balance impairment in women (Cesari et al., 2005; Studenski et al., 2011). These factors may lead to women being more frequently classified as having impaired performance, potentially overestimating sarcopenia severity if sex-specific norms are not used.

Moreover, hormonal changes after menopause can accelerate declines in type II muscle fibres and neuromuscular coordination, further contributing to decreased physical performance in older women (Maltais et al., 2009). As such, using sex-specific reference values or stratified cut-offs for performance measures is recommended, where available, to improve the precision of sarcopenia diagnosis and avoid misclassification.

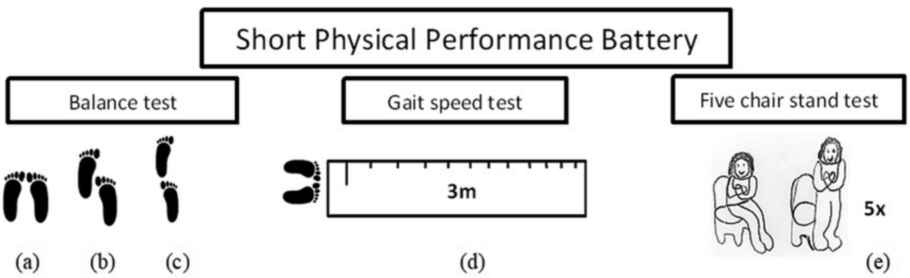

***Figure** 7 Short Physical Performance Battery. a) side-by-side stand; (b) semi tandem stand; (c) tandem stand; (d) the gait speed test and (e) the five chair stand (5CS) test (taken from Paineiras-Domingos et al. (2018))*

3.4 Ultrasound as an alternative tool for sarcopenia diagnosis

Ultrasound imaging is increasingly recognised as a reliable and non-invasive method for assessing muscle mass and quality in the diagnosis and management of sarcopenia. Ultrasound is emerging as a practical alternative to traditional techniques such as DXA and BIA, particularly in settings where these tools are inaccessible (Bianchi et al., 2017; Ticinesi et al., 2018). Unlike DXA, which involves exposure to low levels of radiation, ultrasound poses no radiation risk—an important consideration for older females who may be more sensitive to radiation or require repeated assessments (Ticinesi et al., 2018). Additionally, ultrasound offers several advantages: it is portable, cost-effective, and suitable for use in diverse environments, including clinics, community centers, and even at home. This is particularly beneficial for older adults with limited mobility (Monteiro et al., 2024). While BIA is also portable and easy to administer, its accuracy can be affected by factors such as hydration status and overall body composition. In contrast, ultrasound provides direct visualisation and quantification of muscle architecture, making it less susceptible to such confounding variables (Narici et al., 2021). It provides real-time visualisation of muscle tissue and can be used to measure muscle thickness (MT), fascicle length (FL), pennation angle (PA), cross-sectional area (CSA), and muscle quality (e.g., echogenicity (EI), which reflects intramuscular fat infiltration) (Nijholt et al., 2017; Pillen & van Alfen, 2011; Pillen et al., 2009; Stock & Thompson, 2021). When used correctly, ultrasound provides highly reproducible results, making it suitable for interventions and longitudinal assessments. This allows clinicians to track muscle changes over time, especially in women as they age. This is a key consideration for older women, who may experience a disproportionate loss of muscle quality relative to mass, especially with ageing and hormonal changes after menopause (Geraci et al., 2021; Lu & Tian, 2023).

3.4.1 Muscle mass assessment

In the context of sarcopenia diagnosis by ultrasound (US), key parameters of muscle mass include: 1) FL, which refers to the length of the muscle fibres and is a critical determinant of muscle contractile velocity and range of motion. 2) MT, which represents the distance between the superficial and deep aponeuroses and reflects the amount of contractile tissue within a specific muscle. 3) PA, defined as the angle at which muscle fibres insert into the aponeuroses, plays a significant role in determining muscle force production, particularly in pennate muscles, such as the vastus lateralis. 4) CSA serves as a direct measure of muscle size and volume (Narici et al., 2021). Tracking changes in these parameters over time enables clinicians to assess both hypertrophic and atrophic alterations in muscle architecture. Ultrasound is uniquely capable of distinguishing the specific architectural adaptations that occur during these processes. For instance, changes in FL reflect alterations in the number of sarcomeres arranged in series, which influences muscle excursion and contraction speed. Conversely, changes in PA, MT, and CSA are indicative of sarcomere addition or loss in parallel, affecting the muscle's force-generating capacity (**Figure 8**). This level of structural detail enhances the diagnostic and monitoring capabilities of ultrasound, enabling a precise assessment of muscle remodelling in response to ageing, disease progression, or therapeutic interventions.

Additionally, MT has been shown to have a strong correlation with overall muscle mass and is predictive of functional decline in older adults (Tillquist et al., 2014). Particularly in females, decreased MT in the quadriceps region has been linked to diminished mobility and an increased risk of falls, making it a critical marker in the detection of early sarcopenia (Wang et al., 2018). CSA, which reflects the muscle's capacity to generate force, offers an even more robust representation of muscle volume and functional potential. Studies have demonstrated that reductions in CSA are closely associated with loss of strength, especially in women, who tend to experience qualitative muscle changes (e.g., increased intramuscular fat) at a faster rate than men (Bamman et al., 2000; Trezise et al., 2016). FL, representing the length of muscle fibres between aponeuroses, is a crucial determinant of contractile speed and range of motion. Shortened FL, often observed with ageing and disuse, may indicate architectural remodelling of muscle, which precedes observable atrophy (Abe et al., 2000).

Moreover, to standardise ultrasound-based sarcopenia assessment, researchers have proposed the Ultrasound Sarcopenia Index (USI), a novel metric based on the geometric proportions of muscles (Narici et al., 2021). The USI index has been applied explicitly to the vastus lateralis (VL) muscle, which plays a fundamental role in locomotion and has been observed to decrease drastically with ageing (Kalyani et al., 2014). USI is calculated using ratios between MT and FL, offering a more integrated view of muscle that accounts for age-related architectural changes. For example, lower USI values were consistently associated with lower muscle strength and functional performance, independent of muscle thickness alone.

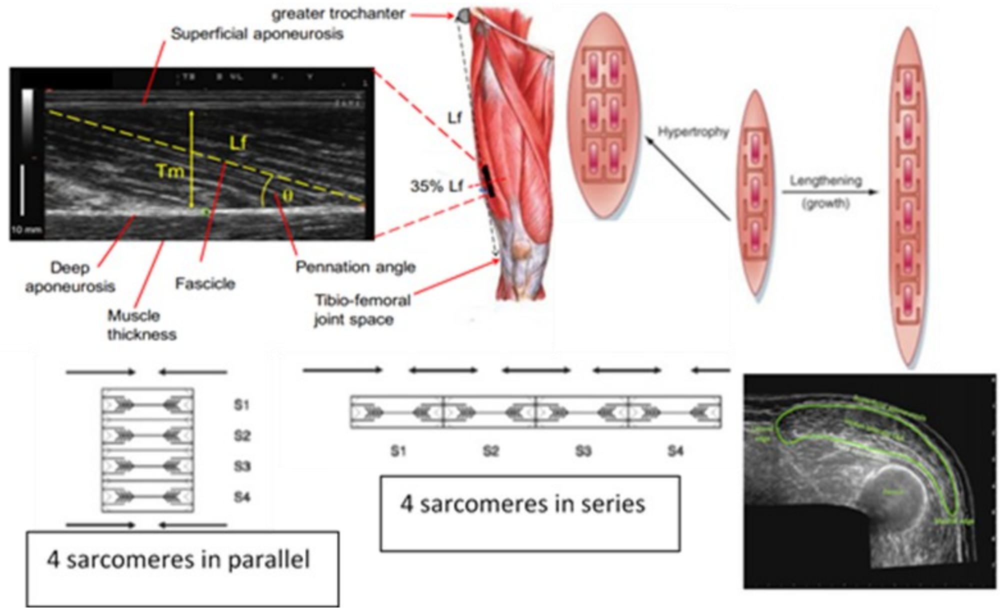

Figure 8 *Muscle architecture of vastus lateralis along with a schematic representation of muscle sarcomeres (adapted from (Adapted from (Stone et al., 2007; Ticinesi et al., 2018))*

3.4.2 Muscle quality assessment

In sarcopenia, loss of muscle strength and function is often accompanied by deterioration in muscle quality, characterized by increased fat infiltration and reduced contractile tissue. Echo intensity (EI), a grayscale value derived from ultrasound imaging (representing the brightness of muscle tissue as seen on ultrasound images), reflects these structural changes and serves as a reliable, non-invasive marker of muscle quality (Fukumoto et al., 2012; Kitagawa et al., 2023; Yuan & Kim, 2024). EI, therefore, refers to the degree of signal reflection that occurs when an ultrasound wave encounters tissues of varying densities, and it is measured by grey-scale analysis (**Figure 9**). When muscle tissue is healthy and predominantly composed of muscle fibres, the EI will be relatively low, as muscle tissue is less reflective than fat. However, as fat infiltration occurs with ageing and sarcopenia, the increased amount of adipose tissue within the muscle results in higher energy EI values. Therefore, higher echo intensity is indicative of reduced muscle quality, as it signifies the presence of intramuscular fat and a decline in muscle functionality (Baek et al., 2023). These changes may be more effectively detected by ultrasound than by other modalities such as DXA or BIA. Higher EI values indicate greater intramuscular fat and connective tissue, even in cases where overall muscle mass appears preserved, making EI a sensitive indicator of early-stage sarcopenia (Watanabe et al., 2013). Age-related increases in EI are particularly evident in older adults, especially postmenopausal women, due to hormonal changes that exacerbate fat infiltration and muscle degradation (Fukumoto et al., 2012; Fukumoto et al., 2018). As sarcopenia progresses, rising EI correlates with poorer muscle function, slower gait speed, and an increased risk of falls (Watanabe et al., 2013). Unlike traditional mass-based measures, EI captures qualitative degeneration, offering a more accurate assessment of functional decline.

A recent systematic review and meta-analysis by Oranchuk et al. (2024) found a moderate negative correlation between quadriceps EI and knee extensor strength ($r = –0.36$), with weaker but still significant correlations with grip strength and gait speed. Tracking EI over time is valuable for detecting sarcopenia early, monitoring its progression, and evaluating the outcomes of interventions, particularly in women, where sex-specific patterns of muscle ageing are pronounced (Oranchuk et al., 2024). These findings highlight the utility of EI as a non-invasive and sensitive marker of muscle quality deterioration and functional decline in ageing populations, especially in females.

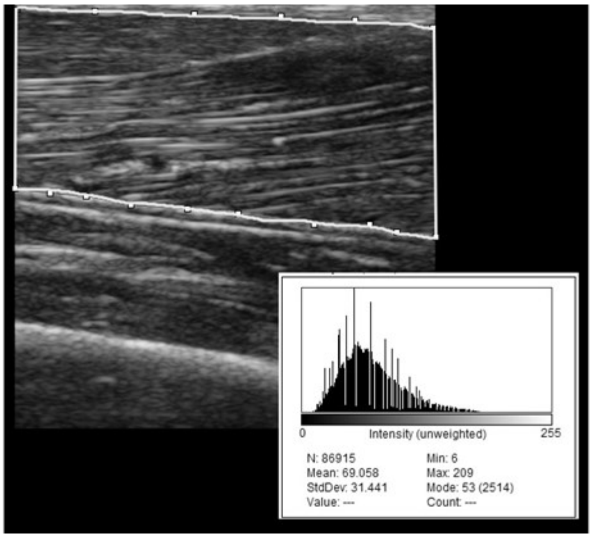

***Figure 9** Muscle architecture of vastus lateralis and measured echo intensity by grey scale analysis*

3.5 Fatigability as an alternative parameter of sarcopenia

In the diagnosis and evaluation of sarcopenia, the traditional emphasis has been placed on assessing muscle mass and strength. While muscle mass and strength remain central diagnostic criteria, they do not fully account for the functional decline experienced by many older adults. Fatigability provides additional insight into muscle function and may serve as a more sensitive indicator of early sarcopenic changes than muscle mass alone (Clark & Manini, 2012; Manini & Clark, 2012). In fact, muscle fatigability may manifest earlier than measurable losses in strength or mass and is closely linked to functional impairments, elevated fall risk, slower recovery after exertion, and reduced independence (Clark & Manini, 2012). Notably, some individuals with preserved muscle mass may still exhibit high levels of fatigue during basic physical tasks, such as walking or prolonged standing, due to factors like mitochondrial dysfunction, impaired neuromuscular transmission, and increased intramuscular fat deposition (Distefano & Goodpaster, 2018). For these reasons, muscle fatigability is gaining attention as a crucial parameter for understanding sarcopenia, especially in older adults (Clark & Manini, 2012).

3.5.1 Pathophysiology of muscle fatigue with ageing and sarcopenia

Muscle fatigue, characterised by a decline in the muscle's ability to generate force or power over time, particularly during sustained or repeated activity, is a multifactorial phenomenon that becomes increasingly prevalent and pronounced with ageing and the onset of sarcopenia (Enoka & Duchateau, 2008). It is influenced by both central (neural) and peripheral (muscular) mechanisms, including metabolic changes, neuromuscular activation, and oxygen delivery to muscle tissues. At the cellular level, ageing muscle exhibits a progressive decline in the number and size of type II (fast-twitch) fibers, which are primarily responsible for quick, powerful movements but are also more susceptible to fatigue. This shift in muscle fibre composition towards a higher proportion of type I (slow-twitch) fibres, although somewhat protective against fatigue, results in decreased muscle strength and power output (Lexell, 1995). One of the central mechanisms underlying this process is mitochondrial dysfunction. Mitochondria in ageing skeletal muscle show reduced oxidative capacity, increased production of reactive oxygen species (ROS), and impaired ATP synthesis, all of which compromise the muscle's energy supply during prolonged activity and accelerate the onset of fatigue (Enoka & Duchateau, 2008; Short et al., 2005).

Additionally, neuromuscular junction (NMJ) degradation contributes significantly to impaired muscle activation. With age, structural and functional changes at the NMJ, including reduced acetylcholine receptor density, synaptic remodelling, and impaired neurotransmitter release, result in less efficient signal transmission, leading to decreased muscle recruitment and increased fatigability (Deschenes, 2011; Goodpaster et al., 2001; Short et al., 2005). Ageing is also associated with motor unit remodelling, characterized by the loss of alpha motor neurons and compensatory reinnervation by surviving neurons. This leads to larger but less finely controlled motor units, further reducing motor precision and endurance (Piasecki et al., 2016). Concurrently, sarcopenia is characterised by increased infiltration of intramuscular fat (myosteatosis) and connective tissue, which impairs muscle contractility and further reduces muscle quality and endurance (Goodpaster et al., 2001). Moreover, systemic factors such as chronic low-grade inflammation ("inflammaging") and anabolic resistance also exacerbate muscle fatigue. Elevated levels of pro-inflammatory cytokines like IL-6 and TNF-α contribute to protein degradation pathways and mitochondrial damage, while anabolic resistance impairs muscle protein synthesis in response to exercise and nutrition (Beyer et al., 2012; Breen & Phillips, 2011). These changes collectively diminish the muscle's ability to sustain force during activity, leading to early onset of fatigue, decreased physical performance, and an increased risk of disability and loss of independence among older adults.

Sex differences in muscle fatigability are evident, with older women generally reporting higher levels of perceived fatigue compared to men, even after adjusting for muscle mass and strength (Hunter, 2014). This may be due to 1) the hormonal changes after menopause, which contributes to mitochondrial dysfunction and increased oxidative stress, exacerbating fatigue during exertion (Tiidus et al., 2013); 2) the lower baseline muscle mass and smaller muscle fibres in women, making them more prone to rapid fatigue in some muscle groups, and 3) greater loss of type II (fast-twitch) muscle fibres, which are essential for high-intensity, quick movements (Hunter, 2014); and 4) higher levels of intramuscular fat infiltration (myosteatosis), which reduces contractile efficiency (Marcus et al., 2010). Ultimately, fatigue in sarcopenic females is both a consequence and a contributor to decreased physical activity, which can lead to a vicious cycle. **Figure 10** shows the relationship between muscle fatigue and sarcopenia in older females.

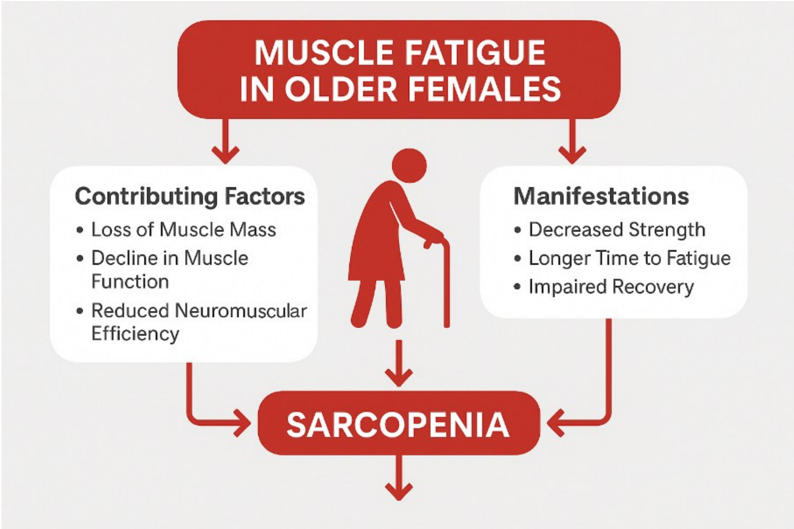

Figure 10 *Muscle fatigue in older females and sarcopenia*

3.5.2 Muscle fatigability assessments

Muscle fatigability can be assessed using various techniques that evaluate the rate of strength decline over time during sustained or repeated contractions. Assessments of fatigability, such as isometric endurance tests, gait speed under load, or self-reported fatigue scale, can be valuable for tracking intervention outcomes and sarcopenia severity (Avin & Law, 2011). Some standard methods include:

Isometric Fatigue Tests:

One of the most common methods is to measure isometric muscle strength during a sustained contraction. For example, grip strength tests or knee extension tests can be held for a specified duration, and the rate of strength loss over time can be used to assess fatigability.

Dynamic Muscle Fatigue:

Dynamic endurance tests, such as repeated stair climbing or walking tests, can be used to measure the rate of muscle fatigue during functional movements. In particular, the 6-minute walk test or gait speed tests are often used to assess both endurance and fatigability (Bohannon, 1997; Laboratories, 2002).

Electromyography (EMG):

EMG can be employed to monitor muscle electrical activity during sustained contractions, providing a more detailed picture of how quickly the muscle fatigues at the neuromuscular level (Farina et al., 2004).

Perceived Fatigue Scales:

Questionnaires or visual analogue scales (e.g., Borg Rating of Perceived Exertion) can be used to subjectively assess the perception of fatigue in daily activities, which correlates strongly with objective measures of muscle fatigability (Borg & Dahlstrom, 1962).

3.6 Exercise strategies for sarcopenia

Exercise is recognized as a fundamental intervention for both the prevention and management of sarcopenia. Older women are more likely to reduce physical activity due to caregiving responsibilities, cultural expectations, or comorbid conditions such as arthritis or osteoporosis (Cruz-Jentoft et al., 2019). This decline in activity, combined with hormonal shifts, can lead to rapid deterioration in muscle mass, strength, and function.

Exercise is one of the most effective non-pharmacological interventions for countering these changes. Regular physical activity elicits distinct physiological and molecular adaptations depending on the type of exercise performed. Resistance training (RT) primarily stimulates muscle protein synthesis through the activation of the mechanistic target of the rapamycin complex 1 signalling pathway. Mechanical loading and muscle contraction lead to the phosphorylation of key regulators, such as Akt and p70S6 kinase, which promote the translation of muscle-specific proteins and result in muscle hypertrophy. RT also improves neuromuscular coordination through increased motor unit recruitment and synchronisation, and it reduces systemic inflammation by decreasing pro-inflammatory cytokines (e.g., TNF-α, IL-6) while increasing anti-inflammatory markers (e.g., IL-10), thereby attenuating muscle catabolism (Cruz-Jentoft et al., 2019; Geng et al., 2023).

In contrast, regular aerobic exercise training (AT) induces adaptations that improve cardiorespiratory fitness and metabolic efficiency. One of the primary molecular responses is the activation of AMP-activated protein kinase and peroxisome proliferator-activated receptor gamma coactivator-1 alpha, which drive mitochondrial biogenesis and enhance oxidative phosphorylation capacity. Central adaptations include increased stroke volume and cardiac output, while peripheral adaptations involve improved capillary density and oxygen extraction in skeletal muscle. Collectively, these changes elevate maximal oxygen uptake (VO_2 max) and improve endurance performance (Shen et al., 2023).

3.6.1 Traditional training strategies for sarcopenia

RT is the most widely recommended form of exercise for sarcopenia management. It involves the use of weights, resistance bands, or bodyweight exercises to stimulate muscle hypertrophy and strength gains. It stimulates muscle hypertrophy, particularly in type II fibres, which are more susceptible to atrophy in women (Westcott, 2012). Physiological benefits of RT include 1) increased muscle protein synthesis, 2) improved muscle strength and power, and 3) enhanced neuromuscular coordination and balance. Recent systematic reviews have demonstrated that resistance training (RT) significantly improves handgrip and lower limb strength, as well as muscle mass, in older adults with sarcopenia (Cheng et al., 2024).

Furthermore, RT has been shown to have a positive impact on functional performance indicators, such as gait speed and the timed up-and-go (TUG) test (Cheng et al., 2024). Programs involving progressive overload have been shown to improve muscle cross-sectional area, strength, and functional performance in postmenopausal women (Fiatarone et al., 1994). Furthermore, resistance training has a positive influence on bone density, metabolic health, and insulin sensitivity, offering additional benefits to ageing females at risk of osteoporosis or metabolic syndrome.

While resistance training is foundational, AT also plays a crucial role in maintaining overall health and functional capacity in individuals with sarcopenia. Aerobic activities, such as walking, cycling, or swimming, enhance cardiorespiratory fitness and aid in fat loss, which is crucial in managing sarcopenic obesity—a phenotype more prevalent among older women (Zamboni et al., 2008). Though less effective at increasing muscle mass compared to resistance training, aerobic exercise improves endurance and reduces systemic inflammation (Baumgartner et al., 1999). Physiological benefits of AT comprise 1) enhanced cardiovascular endurance and oxygen utilization, 2) improved mitochondrial function and insulin sensitivity, and 3) improved healthy body composition by reducing fat mass. AT alone has been associated with improvements in gait speed, fatigue resistance, and walking endurance in older adults (Liao et al., 2019). When combined with resistance training (RT), aerobic exercise contributes to a more comprehensive improvement in physical performance and functional capacity (Yuan & Kim, 2024).

Combining RT and AT provides synergistic benefits, targeting both the muscular and cardiovascular systems, and is particularly effective in reversing or mitigating the effects of sarcopenia by increasing muscle mass and strength, improving endurance, mobility, and balance, and enhancing health-related quality of life. A meta-analysis by (Yuan & Kim, 2024) confirmed that multimodal programs, incorporating both RT and AT, outperform single-modality programs in improving functional status, particularly in measures such as the SPPB and gait speed. Evidence suggests that combined resistance and aerobic training may yield superior results for older women by addressing both muscle hypertrophy and metabolic health (Cadore & Izquierdo, 2013). Such integrated programs improve muscle strength, gait speed, and functional independence, key components of sarcopenia diagnosis. **Table 2** details current training recommendations for older adults.

***Table 2** Current training recommendations for older adults*

Intervention Type	**Benefits**	**Recommended Frequency**
Resistance Training	↑ Muscle mass, ↑ Strength, ↑ Physical function	2–3 times per week
Aerobic Training	↑ Endurance, ↑ Gait speed, ↓ Fat mass	3–5 times per week
Combined Resistance + Aerobic	↑ Strength + Endurance, ↑ Quality of life	RT (2–3×/week) + AT (3–5×)

3.6.1 Physical benefits of dance and martial arts

Dance and martial arts provide engaging, structured, and socially supportive environments that align well with the preferences of many older females. These activities are often perceived as more enjoyable and less intimidating than traditional resistance training, thereby increasing long-term adherence (Gill et al., 1997; Keogh et al., 2009; Organization, 2015). The rhythmic, music-based, and often group-oriented nature of these activities can enhance motivation and reduce exercise dropout rates among older women.

Both dance and martial arts incorporate multi-directional, weight-bearing, and balance-challenging movements, which are essential for older women who face a higher risk of falls and fractures due to age-related declines in bone mineral density and neuromuscular control (Organization, 2015). Dance exercise incorporates aerobic and strength elements in a low-impact format that improves gait stability, coordination, and leg strength—key factors in mitigating sarcopenia and fall risk. On the other hand, martial arts, particularly styles adapted for older adults, emphasise postural control, lower-limb engagement, and core stability —all of which contribute to the preservation of functional independence.

Moreover, cognitive decline and mental health challenges, including anxiety and depression, are more prevalent in older females and may be exacerbated by sarcopenia-related disability (Yogesh et al., 2025). Dance and martial arts require mental engagement through memorising sequences, reacting to stimuli, and practising mindfulness or meditative components (e.g., in Tai Chi or kata practice), which can stimulate cognitive functions and enhance mental well-being (Witte et al., 2016).

Additionally, martial arts can promote self-efficacy, discipline, and confidence, which are particularly empowering for older women who may face societal stereotypes of fragility or dependency in later life. Older females are at greater risk of social isolation due to widowhood, retirement, or caregiving burdens. Dance and martial arts classes promote community and social bonding, which can help combat loneliness and enhance emotional resilience (McIntyre et al., 2018). This social component is also a key factor in adherence, which is critical to realising long-term benefits in sarcopenia prevention. Both dance and martial arts can be easily modified to accommodate various fitness levels and comorbidities commonly seen in older females (e.g., arthritis and cardiovascular limitations). However, supervision by trained instructors, particularly those experienced in working with older adults, is essential to ensure safety and proper technique.

4 Methodology

This randomised, three-arm, controlled trial was conducted at the Faculty of Physical Education and Sport, Charles University, Prague, from May 2021 to December 2022. The study was approved by the Charles University, Faculty of Physical Education and Sport Ethics Committee (doc. No. 245/2020) and conformed to the ethical standards set by the Declaration of Helsinki (World Medical Association. This study was part of a larger research project registered on clinicaltrials.gov (registration ID NCT05363228, 03/05/2022). This part of the study focused solely on the effects of dance therapy and martial arts on sarcopenia parameters in older female participants aged 65 years and over.

4.1 Design of the study

Female study volunteers were randomly assigned to a dance group (DG), a martial arts group (MaG) and a control group (CG), with dance intervention lasting 12 weeks (90 minutes per session, 2x a week). The dance intervention took place from September to November 2021, and the martial arts intervention took place from September to November 2022. **Figure 11** shows a general schematic representation of the study design. Further details on the original trial design can be found in our published paper (Hola et al., 2024).

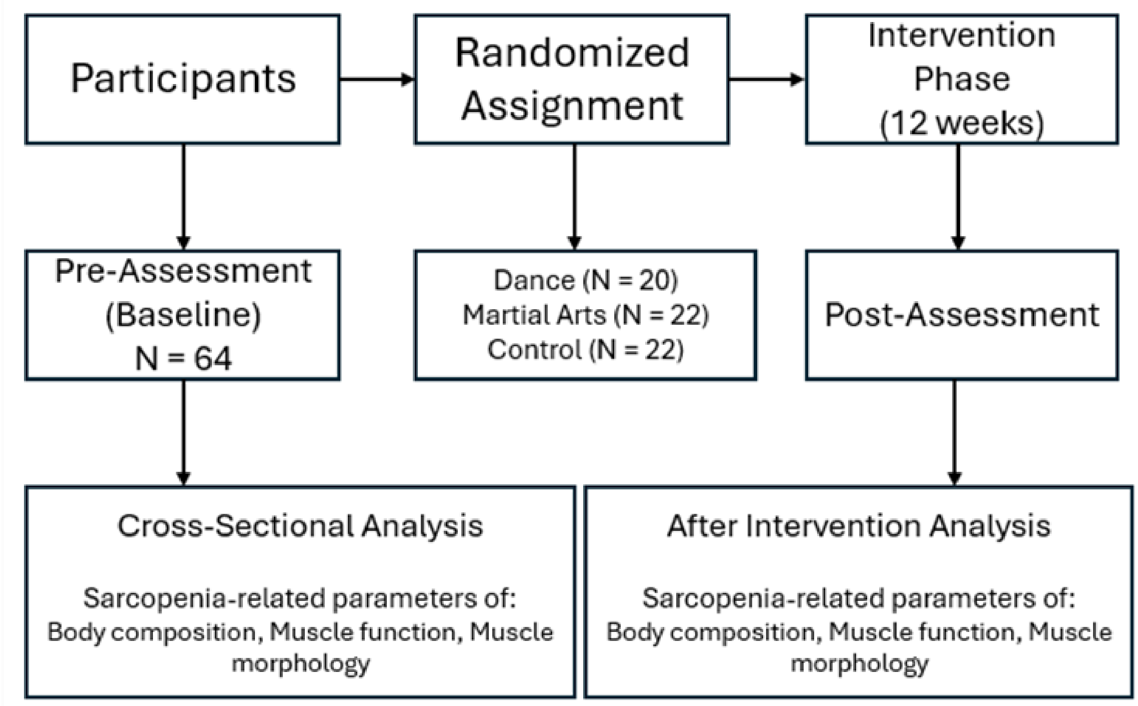

Figure 11 *Study design*

4.2 Study participants

The female study volunteers were recruited from the larger research study group, which also included male participants, as detailed previously in Hola et al. (2024). Sixty-four independently living older female volunteers participated in this study. All female volunteers were considered healthy and suitable for the study after meeting the exclusion criteria detailed in **Table 3**. All volunteers provided written informed consent to participate in the study (Appendix 2). We selected the sample size a priori based on power analysis using G*Power 3.1. Based on previous findings, we determined a medium effect size ($f^2 = 0.15$) and statistical significance of $\alpha = 0.05$, with 80% power of the test.

***Table 3** Exclusion criteria applied for this study*

- Active cardiovascular disease: no stage 2 hypertension (diastolic blood pressure > 90 and systolic > 150 mmHg), angina, heart failure (class III/IV), arrhythmia, right-to-left cardiac shunt or recent cardiac event
- Cerebrovascular disease: previous stroke, aneurysm (large vessel or intracranial)
- Respiratory diseases, including pulmonary hypertension and asthma
- Metabolic disease: hyper and hypoparathyroidism, untreated hyper and hypothyroidism, Cushing's disease, types 1 or 2 diabetes
- Active inflammatory bowel or renal disease
- Malignancy
- Recent steroid treatment (within 6 months) or hormone replacement therapy
- Musculoskeletal or neurological disorder
- Muscular or osteoarticular injury in the previous 6 months

4.3 Somatic-based exercise interventions

Briefly, both intervention sessions were conducted consistently within the same seasonal period (September–November) and at the same indoor venue, ensuring standardised environmental conditions across all sessions. Although the two interventions – martial arts and dance - differed in structure and instructional focus, they shared similar physiological characteristics.

Both exercise programs were characterised by predominantly aerobic and intermittent energy expenditure, with variable intensities and the occasional activation of the anaerobic alactic energy system during brief periods of higher exertion. Across both interventions, session intensity ranged from low during the warm-up and cool-down phases to moderate or moderately high during peak activity. The movement patterns involved the dynamic activation of global muscle groups, with a particular emphasis on postural control, lower-body strength, core engagement, and functional movement patterns suitable for older adults.

Despite these shared features, it is essential to note that this study did not aim to compare the two intervention modalities against each other. Instead, each was evaluated independently compared to a non-intervention control group to examine their specific effects on selected outcome measures. The interventions were thus designed to be comparable in duration and general physical demand. However, they were conceptually distinct in their approach - one emphasising structured, scenario-based defensive skills and the other focusing on creative, expressive movement grounded in somatic principles.

Both interventions were implemented with safety, age appropriateness, and psychological engagement in mind, incorporating progressive physical loads, sufficient rest intervals, and activities that simultaneously challenged both physical and cognitive capacities in the senior population.

4.3.1 Dance intervention

The dance intervention implemented in this study was based on the principles of Laban Movement Analysis (LMA) and Bartenieff Fundamentals, methodologies developed initially by Rudolf Laban and Irmgard Bartenieff, respectively (Bartenieff & Lewis, 1980; Hackney, 2001). LMA provides a comprehensive framework for observing, describing, and understanding human movement through key components such as Body, Effort, Shape, and Space (BESS), facilitating a nuanced approach to expressive movement (Bartenieff & Lewis, 1980; Newlove & Dalby, 2004). Bartenieff Fundamentals, closely aligned with LMA, emphasises the integration of anatomical connectivity, developmental movement patterns, and efficient body use to support expressive and functional movement (Hackney, 2001).

Each 90-minute session followed a structured yet flexible format tailored to promote physical engagement and creative expression. Sessions began with a 15-minute welcome circle to foster attentiveness, body awareness, breath control, grounding, and connection to the environment. Through observational exercises and simple rhythmic patterns, participants were encouraged to develop a mindful approach to movement from the outset.

Following the opening segment, a 30-minute warm-up focused on anatomical awareness and alignment. Drawing on Bartenieff's developmental movement sequences, participants engaged in exercises that addressed the skeletal, muscular, fascial, and integumentary systems through guided touch, stretching, and gentle resistance. This phase prepares the body for more dynamic movement exploration by enhancing proprioceptive awareness and internal connectivity.

The central portion of the session consisted of 30 minutes of controlled improvisation guided by various choreographic prompts and movement scores. Participants explored a range of spatial trajectories, movement qualities, expressive shaping, walking patterns, use of props, phrasing, and relational dynamics. The improvisational work was scaffolded through verbal cues, storytelling, symbolic imagery, and metaphor, encouraging personal interpretation and active engagement. Initially, the focus was placed on mirroring and imitation to support movement accuracy and spatial orientation. As sessions progressed, participants were gradually invited to engage in more spontaneous, creative, and individually expressive movement practices.

To conclude each session, a 15-minute cool-down period was provided, emphasising the integration of both physiological and psychological aspects. This phase included breathing exercises and moments of self-reflection, often accompanied by a verbal sharing circle. Participants were invited to articulate their experiences, promoting deeper awareness and consolidation of learning. Verbal reflection also served as a space for reinforcing key elements of the session and building a sense of community.

All sessions were facilitated by a qualified dance professional trained in Laban/Bartenieff methods. The intervention was designed to be inclusive, adaptable, and supportive, ensuring a psychologically safe and physically appropriate environment for all participants. A comprehensive account of the intervention's structure, objectives, and instructional content is available in Polanská's doctoral dissertation (Polanska, 2024).

4.3.2 Martial arts intervention

The self-defence training unit employed in this study was designed to be comprehensive and systematically structured, incorporating all essential components necessary for a safe and effective physical education session tailored to seniors. The training session lasted approximately 90 minutes and was divided into three main phases: an introductory warm-up, a central segment focused on technique and scenario practice, and a final relaxation and recovery period.

The introductory phase, lasting 10 to 15 minutes, was intended to gradually prepare participants for physical activity. It included basic exercises such as walking around the gym's perimeter, circular joint movements, and stretching of major muscle groups. These activities aim to gently activate the musculoskeletal system and reduce the risk of injury during the subsequent physical exertion.

The main phase lasted approximately 60 minutes and focused on practising self-defence techniques, falls, and simulated crisis situations. This part was further divided into three segments. The first involved practising basic falls and protective stances—forward, backwards, and sideways—on soft mats, emphasising proper technique and head protection to minimise the risk of injury (Chvátalová et al., 2012). The second segment included basic grappling exercises, such as partner-based tug-of-war and push drills, as well as simple reaction tasks aimed at unbalancing a partner through gentle pressure. These activities were designed to develop stability, balance, and body awareness in a playful and engaging manner (Fojtík, 1994). The third segment focused on model situations in which participants responded to simulated scenarios, such as attempted theft or verbal threats, with the assistance of helpers. The emphasis here was on staying calm under pressure and applying the techniques learned in a controlled and supportive environment.

The final phase, lasting 15 to 20 minutes, concentrated on relaxation and physical recovery. It began with light stretching exercises targeting the back, lower limbs, and arms, followed by deep breathing and visualisation techniques to promote a sense of calm and relaxation. The session concluded with a brief reflection and discussion period during which participants could share their impressions, and instructors reinforced key learning points (Neide, 2010). The structure of the training unit was consistent with current recommendations for physical activity in older adults, which stress the importance of gradual warm-up and cool-down phases to prevent injury and support recovery (Roberson et al., 2015).

The content was carefully adapted to the physical and psychological capabilities of the senior population, with particular attention paid to creating a safe, respectful, and supportive training environment. A comprehensive account of the intervention's structure, objectives, and instructional content is available in Holá's doctoral dissertation (Holá, 2025).

4.4 Pre and post-assessments

Table 4 below summarises all the evaluation tests, detailing the tools used and measurable endpoints.

Table 4 *All the evaluation tests*

Assessment tests	Specific tools	Measurable endpoints – evaluation of:
Body composition	BMI (weight, height) BIA	Total fat mass Estimation of fat and muscle mass
Muscle Function	Chair stand Gait speed Handgrip strength Maximum Lower Voluntary Isometric Contraction Fatigability	Functional abilities and screening tools for sarcopenia Lower limb muscular strength Fatigue
Muscle morphology	Ultrasound of the vastus lateralis	Muscle architecture and echo intensity

4.4.1 Body composition

Height was measured using a Seca 213 portable stadiometer, and weight and body composition were measured using a Professional Body Composition Analyser InBody 720 (Biospace Co., Ltd) Korea. The following parameters were analysed: body mass index (BMI), skeletal muscle mass (SMM), skeletal muscle index (SMI), and percentage of fat.

4.4.2 Muscle function

Maximal upper and lower isometric muscle strength was measured using dynamometry at the dominant and right sites. Handgrip strength (HG) was measured by TKK5401 (Takei

Scientific Instruments Co., Ltd., Niigata, Japan) in a standing position with the shoulder adducted at 0° flexion, forearm in a neutral position, and wrist in a comfortable position, respecting the range of max 30º extension. Maximal lower voluntary isometric contraction (MVC) and fatigability were measured using the Humac NORM, CSMi, Stoughton, MA.

Fatigability was measured using the Fatigue Index FATI3 protocol developed by Surakka et al. (2005). Volunteers sustained isometric contractions for 30 s, and the torque (Nm) versus time (s) curve was used to assess fatigue. The key metric was the change in torque from the Time Point of Maximum (TPM) muscle torque, which represents the peak of the contraction, to the end of the 30 seconds. In this setup, the Fatigue Index (FATI3) was calculated by measuring the decrease in torque over time from the point of maximum strength. The time of maximum muscle torque (TPM) was defined as the highest mean value within a 1-second window from 0 to 5 seconds. The TPM was used as the starting point for calculating the area under the force-time curve (AUFC). The AUFC from this point to the end of the contraction (30 s) was divided by the hypothetical AUFC that would be obtained if the patient maintained the same maximal force until the end of the 30 s. The result is the $AUFC_{TPM}$. The final FATI3 value was obtained as $100\% \times [1 - (AUFC_{TPM\text{-}30}/(F_{max,\ 0\text{-}5} \times (TPM\text{-}30)))]$ (**Figure 12**).

MVC and fatigability were measured once after a familiarisation measure was executed at 30% of the participant's perceived maximal strength. The handgrip test was repeated three times, and the best performance value was used for subsequent statistical analyses.

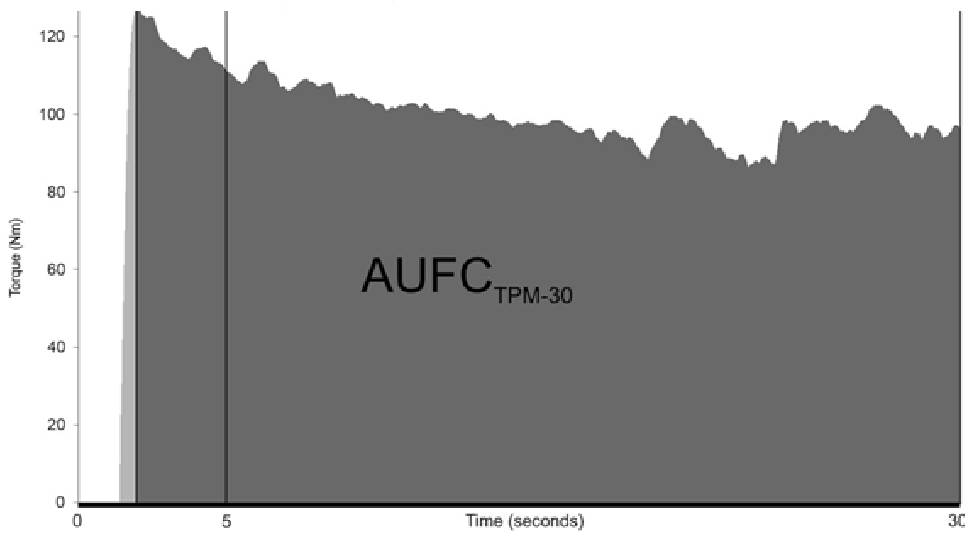

***Figure 12** The area under the force versus time curve (AUFC) calculation*

4.4.3 Muscle morphology

Ultrasound assessments were conducted using a B-mode ultrasound device (Mindray M5) with a 5 cm, 3-11 MHz linear-array probe. The same researcher evaluated the VL muscle structure and EI at rest in all participants, following the standardised method by Ticinesi et al. (2018). The consistency of measurements across different days was assessed using the intraclass correlation coefficient (ICC) (Jandova et al., 2020) for two separate measurement sessions. The ICC demonstrated excellent reliability for all parameters measured, with values ranging from 0.96 to 0.99.

During the ultrasound procedure, participants lay supine on an examination table with their knees fully extended (anatomical zero). Measurements of muscle architecture, including fibre fascicle length (FL), pennation angle (PA), muscle thickness (MT), and EI, were taken on the right side of the resting VL at 65% of the distance from the caudal part of the greater trochanter to the lateral femoral condyle, along the mid-sagittal axis. For EI, the settings applied to all subjects were a depth of 50 mm, a frequency of 10 MHz, and a gain of 50 dB. Three longitudinal images of the VL were captured for each measurement and stored for subsequent analysis. All images were analyzed using NIH ImageJ software. The FL/MT ratio was employed to compute the 'ultrasound sarcopenia index' (USI) (Narici et al., 2021). EI was calculated using the standard histogram function with a grayscale range from 0 (black) to 255 (white), representing the mean and standard deviation (SD) of each histogram.

4.5 Data analysis

4.5.1 Intervention Study

For the intervention study, means and standard deviations were computed for continuous variables, and proportions were reported for categorical variables. The Kruskal-Wallis test was used for continuous data, and the chi-squared test was used for categorical data to compare baseline characteristics between groups. Within-group changes from pre- to post-intervention were assessed using the Wilcoxon signed-rank test. Generalised linear models (GLMs) were employed to evaluate the effect of the intervention. These models were adjusted for participants' age, height, and baseline (pre-intervention) values of the dependent variables. The unstandardised regression coefficient (B) from the GLM was used to quantify the intervention effect. Statistical significance was set at $\alpha = 0.05$ for all analyses.

4.5.2 Cross-sectional Study

Descriptive statistics were computed for all continuous variables, including means and standard deviations (SD). Pearson correlation coefficients were calculated to assess the relationships between variables. The primary analytical approach involved hierarchical multiple regression models. In the first hierarchical regression analysis, we investigated the influence of age, EI, and HG on MVC. In the second model, we examined the effects of age, EI, and HG on the fatigability index. HG and gait speed were selected as explanatory variables due to their highest observed correlations with the dependent variables. Each hierarchical regression model consisted of three sequential blocks. In the first block, age was included as the sole explanatory variable. The second block introduced EI, and the third added HG or GS to assess whether these variables were significantly independent predictors of MVC and fatigability index. To evaluate the proportion of variance explained by each model, we calculated the coefficient of determination (R^2) and the change in R^2 with the addition of new predictors. Standardised regression coefficients (β) were reported for each predictor in all model blocks to assess their individual contributions. A p-value of less than 0.05 was considered statistically significant. All statistical analyses were conducted using IBM SPSS Statistics version 24.

5 Results

5.1 Effects of exercise interventions

Sixty-four older females were randomly assigned to one of three groups: the dancing group (DG), the martial arts group (MaG), and the control group (CG). Fifty females completed the interventions (see **Table 5** for the retention rates across the groups). The mean age of participants in the DG was 69.7 (3.7), in the MaG was 71.2 (4.5), and in the CG was 70.3 (4.1). **Table 5** summarises the baseline descriptive characteristics of the female volunteers across the three groups. No significant differences were found among the groups in terms of age, height, weight, body mass index (BMI), or overall retention rates ($p > 0.05$).

Table 5 *Descriptive characteristics and adherence of the study participants per group*

	DG n = 20	**MaG** n = 22	**CG** n = 22	**Sig.**
Age (years)	69.7 (3.7)	71.2 (4.5)	70.3 (4.1)	0.456
Height (cm)	164.6 (7.5)	162.5 (7.3)	163.4 (6.3)	0.756
Weight (kg)	72.5 (11.8)	67.6 (12.2)	71.1 (15.4)	0.386
BMI (kg.m^{-2})	26.9 (4.5)	25.6 (3.7)	26.6 (5.0)	0.754
Total retention rate (%)	85.0	63.6	86.4	0.127

Note: Data are presented as mean (SD) for continuous data and as proportions for categorical data; DG = dancing group; MA = martial arts; CG = control group; BMI = Body Mass Index; Sig and calculated either the Kruskal-Wallis test for continuous or Chi-Square for categorical data.

For the muscle morphology parameters, both DG and MaG demonstrated significant ($p < 0.05$) improvements in PA post-intervention: 11.8 (2.2) - 12.4 (1.9) and 13.4 (1.4) - 14.3 (1.1), which was significantly different ($p < 0.05$) when compared to the control group [Δ 0.61 (1.0) - 0.82 (0.6)], respectively. Moreover, the MaG group exhibited a statistically significant ($p < 0.05$) increase in MT [1.56 (0.3) - 1.69 (0.3) cm] and FL [6.3 (0.7) - 6.6 (0.7) cm], which was significant ($p < 0.05$) when compared to the CG group [Δ 0.13 (0.1) and 0.73 (1.7), respectively]. A significant change ($p < 0.05$) in EI in both groups [Δ -3.51 (12.5) for DG and -2.94 (6.7) for MaG] and in USI in the MaG was also found [Δ -0.14 (0.3)] when compared to the CG. A significant decrease ($p < 0.05$) pre- and post- was found in CG for PA [13.3 (1.8) - 12.6 (1.7)], MT [1.63 (0.3) - 1.56 (0.4) cm] and FL [6.6 (0.6) - 6.4 (0.7) cm].

No significant pre-post improvements were observed among the three groups for the body composition parameters. However, the MaG group showed a significant change ($p < 0.05$) in BMI, SMM, and SMI [Δ -0.46 (0.9), -0.25 (0.5), and -0.10 (0.2), respectively] compared to the CG.

For the muscle function parameters, only a pre-post improvement in fatigability was observed in the MaG group: 0.89 (0.1) - 0.84 (0.1); however, the change was not significant compared to the CG group.

Table 6 details the pre-and post-intervention measures and changes (Δ) in a range of variables grouped into three categories: muscle morphology, body composition, and muscle function.

Table 6 *Pre and post-measures and changes in all tested variables*

	DG (n = 17)		**MaG (n = 14)**		**CG (n = 19)**		**DG (n = 17)**	**MaG (n = 14)**	**CG (n = 19)**
	Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Δ**	**Δ**	**Δ**
Muscle Morphology									
Pennation angle (in°)	11.8 (2.2)	**12.4 (1.9)***	13.4 (1.4)	**14.3 (1.1)***	13.3 (1.8)	**12.6 (1.7)***	**0.61 (1.0)#**	**0.82 (0.6)#**	-0.73 (0.8)
Muscle thickness (cm)	1.70 (0.3)	1.70 (0.3)	1.56 (0.3)	**1.69 (0.3)***	1.63 (0.3)	**1.56 (0.4)***	**-0.00 (0.1)#**	**0.13 (0.1)#**	-0.07 (0.1)
Fiber length (cm)	6.57 (0.7)	6.65 (0.6)	6.3 (0.7)	**6.6 (0.7)***	6.6 (0.6)	**6.4 (0.7)***	0.08 (0.3)	**0.73 (1.7)#**	-0.18 (0.2)
Ultrasound sarcopenia index	3.96 (0.7)	4.00 (0.6)	4.1 (0.5)	3.9 (0.5)	4.1 (0.7)	4.2 (0.8)	0.04 (0.3)	**-0.14 (0.3)#**	0.10 (0.3)
Echo Intensity (AU)	66.8 (16.4)	63.3 (8.4)	66.6 (6.5)	63.6 (10.6)	63.5 (16.8)	69.6 (16.3)	**-3.51 (12.5)#**	**-2.94 (6.7)#**	6.12 (14.9)
Body composition									
BMI ($kg.m^{-2}$)	26.0 (3.8)	25.9 (3.8)	25.4 (3.7)	25.0 (3.7)	25.2 (3.6)	25.3 (3.4)	-0.05 (1.0)	**-0.46 (0.9)#**	0.07 (0.5)
SMM (kg)	25.1 (3.5)	25.6 (3.1)	23.3 (3.4)	23.1 (2.7)	24.8 (3.4)	24.9 (3.1)	0.10 (0.7)	**-0.25 (0.5)#**	0.17 (0.9)
SMI ($kg.m^{-2}$)	9.21 (0.8)	9.26 (0.7)	8.9 (0.8)	8.8 (0.8)	9.3 (0.9)	9.3 (0.7)	0.05 (0.3)	**-0.10 (0.2)#**	0.06 (0.3)
Fat (%)	33.3 (7.1)	33.3 (6.7)	23.1 (7.4)	22.6 (7.1)	21.8 (7.8)	21.8 (7.6)	0.02 (3.1)	-0.56 (2.0)	0.00 (1.7)
Muscle Function									
Handgrip (kg)	26.1 (5.7)	27.0 (5.1)	24.6 (2.9)	25.1 (2.7)	28.0 (5.6)	28.4 (5.5)	0.85 (2.7)	0.54 (2.0)	0.42 (2.2)
Grip to BMI ($kg.kg.m^{-2}$)	1.03 (0.3)	1.06 (0.3)	0.99 (0.2)	1.02 (0.2)	1.12 (0.2)	1.13 (0.2)	0.04 (0.1)	0.04 (0.1)	0.01 (0.1)
MVC (Nm)	130.2 (28.5)	133.7 (32.4)	109.3 (22.9)	114.6 (22.8)	124.4 (26.7)	124.4 (32.1)	3.54 (29.1)	5.24 (15.7)	0.01 (22.0)
Fatigability index	0.87 (0.1)	0.84 (0.1)	0.89 (0.1)	**0.84 (0.1)***	0.83 (0.1)	0.85 (0.1)	-0.03 (0.1)	-0.06 (0.1)	0.01 (0.1)
Gait speed ($m.s^{-1}$)	1.19 (0.2)	1.25 (0.3)	1.26 (0.2)	1.22 (0.2)	1.30 (0.2)	1.32 (0.2)	0.05 (0.2)	-0.04 (0.2)	0.03 (0.4)
Chair stand (s)	7.01 (1.6)	6.71 (2.0)	8.2 (1.7)	7.8 (1.6)	7.1 (2.8)	6.7 (2.0)	-0.38 (2.0)	-0.41 (2.1)	-0.43 (2.2)

Note: data are presented as mean (SD); MA = martial arts; CG = control group; BMI = body mass index; SMM = skeletal muscle mass; SMI = skeletal muscle index; MVC = maximal lower voluntary isometric contraction. *Wilcoxon signed ranks test $p < 0.05$; #Significantly different from CG by GLMs adjusted for age, height and pre-intervention measurement $p < 0.05$

5.1 Cross-sectional data analysis

A total of 64 older female volunteers (mean age: 70.4 ± 4.1 years) were assessed for anthropometric, muscular, and functional parameters. They had an average height of 163.5 ± 7.0 cm and a weight of 70.3 ± 13.2 kg, corresponding to a mean body mass index (BMI) of 26.3 ± 4.4 kg/m². Complete descriptive and baseline statistics are summarised in **Table 7** below.

***Table** 7 Demographic and baseline parameters of all study participants*

Variable	Subjects (N = 64)
Age (years)	70.4 (4.1)
Height (cm)	163.5 (7.0)
Weight (kg)	70.3 (13.2)
BMI (kg/m^2)	26.3 (4.4)
MVC (Nm)	120.8 (29.3)
Fatigability index	0.87 (0.1)
SMM (kg)	25.0 (3.5)
Fat (%)	33.6 (7.0)
EI (AU)	65.7 (13.3)
Pennation angle (in°)	12.9 (1.8)
Muscle thickness (cm)	1.6 (0.3)
Fiber length (cm)	6.6 (0.7)
Ultrasound sarcopenia index	4.1 (0.6)
Handgrip (kg)	26.5 (5.1)
Grip to BMI (kg/kg/m^2)	1.02 (0.2)
Gait speed (m/s)	1,22 (0.2)
Chair stand (s)	7.6 (2.2)

Note: data are presented as mean (SD); BMI = Body Mass Index; MVC = maximal lower voluntary isometric contraction; SMM = Skeletal Muscle Mass; EI = Echo Intensity

A Pearson correlation analysis was conducted to investigate the relationships between variables related to muscle function, morphology, and body composition. MVC was positively correlated with fatigability index (FI; $r = 0.370$, $p < 0.001$), muscle thickness (MT; $r = 0.335$, $p < 0.001$), fibre length (FL; $r = 0.158$, $p < 0.05$), handgrip strength (HG; $r = 0.462$, $p < 0.001$), and grip strength relative to BMI (HG/BMI; $r = 0.405$, $p < 0.001$). Conversely, MVC was negatively correlated with echo intensity (EI; $r = -0.406$, $p < 0.001$) and the ultrasound sarcopenia index (USI; $r = -0.284$, $p < 0.05$). Echo intensity (EI), an indicator of intramuscular fat and fibrous tissue, was negatively associated with pennation angle (PA; $r = -0.254$, $p < 0.05$), HG/BMI ($r = -0.354$, $p < 0.001$), and chair stand performance (CS; $r = -0.304$, $p < 0.05$). SMM was positively correlated with muscle thickness ($r = 0.289$, $p < 0.05$) and HG ($r = 0.522$, $p < 0.001$) while negatively correlated with USI ($r = -0.249$, $p < 0.05$). MT showed a strong positive correlation with fibre length ($r = 0.709$, $p < 0.001$) and a strong negative correlation with USI ($r = -0.788$, $p < 0.001$), indicating its potential utility in evaluating muscle health and risk of sarcopenia. HG was strongly correlated with HG/BMI ($r = 0.722$, $p < 0.001$). Additionally, HG/BMI showed a positive correlation with gait speed (GS; $r = 0.354$, $p < 0.001$), indicating that relative grip strength may reflect overall functional capacity. The fat percentage (Fat%) showed negative correlations with HG/BMI ($r = -0.590$, $p < 0.001$) and CS ($r = -0.329$, $p < 0.001$), while being positively associated with EI ($r = 0.309$, $p < 0.05$). These associations suggest that higher adiposity is linked to poorer muscle quality and physical function. The complete correlation matrix for selected variables is present in **Table 8**.

Table 9 displays the results of hierarchical regression models predicting MVC in women aged 65 and older using the enter method. In Model 1, age was a significant negative predictor of knee extension strength ($\beta = -0.336$, $p = 0.007$), accounting for 11.3% of the variance ($R^2 = 0.113$), indicating that strength declines with increasing age. Model 2 introduced echo intensity (EI) as a second predictor. The addition of EI significantly improved the model ($\Delta R^2 = 10.8\%$, $p = 0.005$), increasing the explained variance to 22.1%. Both age ($\beta = -0.246$, $p = 0.040$) and EI ($\beta = -0.341$, $p = 0.005$) remained significant predictors, suggesting that poorer muscle quality (higher EI) is associated with lower MVC, independent of age. In Model 3, handgrip strength (HG) was added as a third predictor. This model explained 34.7% of the variance ($R^2 = 0.347$), with a significant additional contribution ($\Delta R^2 = 12.6\%$, $p = 0.001$). In this final model, EI ($\beta = -0.308$, $p = 0.006$) and HG ($\beta = 0.371$, $p = 0.001$) were significant predictors, whereas age was no longer significant ($\beta = -0.148$, $p = 0.190$). This suggests that muscle quality and upper-limb strength are more robust predictors of lower-limb strength than age alone in this population.

Table 8 *Correlation matrix of selected variables*

	MVC	FI	SMM	Fat%	EI	PA	MT	FL	USI	HG	HG to BMI	GS	CS
MVC	1	**0.370****	0.220	-0.093	**-0.406****	0.154	**0.335****	0.158	**-0.284***	**0.462****	**0.405****	0.124	-0.113
Fatigability index		1	0.016	-0.200	**-0.322****	-0.059	0.128	-0.061	-0.160	0.219	**0.293***	**0.388****	-0.164
SMM			1	0.189	0.128	0.079	**0.289***	0.177	**-0.249***	**0.522****	-0.104	-0.092	0.244
Fat%				1	**0.309***	0.009	**0.248***	0.119	-0.229	0.013	**-0.590****	**-0.329****	**0.305***
EI					1	**-0.254***	-0.156	0.040	0.233	-0.158	**-0.354****	**-0.304***	0.198
Pennation angle						1	**0.464****	**0.349****	**-0.432****	0.160	0.075	0.178	0.055
Muscle thickness							1	**0.709****	**-0.788****	0.320	0.025	0.014	0.010
Fiber length								1	-0.154	0.228	0.006	-0.119	-0.143
Ultrasound sarcopenia index									1	-0.204	0.001	-0.111	-0.139
HG										1	**0.722****	0.148	0.075
Grip to BMI											1	**0.354****	-0.160
Gait speed												1	-0.228
Chair stand													1

Note: MVC = maximal lower voluntary isometric contraction; SMM = skeletal muscle mass; BMI = Body mass index; EI = Echo Intensity; HG = Handgrip; FI = fatigability index; USI = ultrasound sarcopenia ratio
*p<0.05; **p<0.001

***Table 9** Hierarchical regression models for maximal lower voluntary isometric contraction*

Model		MVC Beta	Sig.
1	Age	-0.336	0.007
	R^2	11.3 %	0.007
2	Age	-0.246	0.040
	EI	-0.341	0.005
	R^2	22.1 %	0.007
	R^2 change	10.8 %	0.005
3	Age	-0.148	0.190
	EI	-0.308	0.006
	HG	0.371	0.001
	R^2	34.7 %	0.005
	R^2 change	12.6 %	0.001

Note: MVC = maximal lower voluntary isometric contraction EI = Echo Intensity; HG = Handgrip

Table 10 summarises the hierarchical regression models predicting the fatigability index in women aged 65 years and older using the enter method. In Model 1, age was a significant negative predictor of fatigability ($\beta = -0.257$, $p = 0.041$), explaining 6.6% of the variance ($R^2 = 0.066$). This indicates that younger individuals in the cohort tended to report higher levels of fatigability. In Model 2, echo intensity (EI) was added as a second predictor. This addition significantly improved the model ($\Delta R^2 = 6.9\%$, $p = 0.031$), increasing the explained variance to 13.5%. In this model, EI was a significant negative predictor ($\beta = -0.273$, $p = 0.031$). At the same time, age lost its statistical significance ($\beta = -0.184$, $p = 0.141$), suggesting that poorer muscle quality (higher EI) may partially mediate the relationship between age and fatigability. Model 3 included gait speed (GS) as a third predictor. This model accounted for 20.2% of the variance ($R^2 = 0.202$), with an additional significant contribution ($\Delta R^2 = 6.7\%$, $p = 0.029$). In the final model, GS emerged as a significant positive predictor ($\beta = 0.289$, $p = 0.029$), indicating that higher gait speed was associated with greater fatigability index values. EI was no longer significant at the 0.05 level ($\beta = -0.211$, $p = 0.090$), and age remained non-significant ($\beta = -0.086$, $p = 0.501$).

Table 10 *Hierarchical regression models for Fatigability index*

Model		**Fatigability index** **Beta**	**Sig.**
1	Age	-0.257	0.041
	R^2	6.6 %	0.041
2	Age	-0.184	0.141
	EI	-0.273	0.031
	R^2	13.5 %	0.012
	R^2 change	6.9 %	0.031
3	Age	-0.086	0.501
	EI	-0.211	0.090
	GS	0.289	0.029
	R^2	20.2 %	0.003
	R^2 change	6.7 %	0.029

Note: EI = Echo Intensity; GS = Gait Speed

6 Discussion

6.1 Effects of exercise interventions on sarcopenia parameters

This randomised controlled trial investigated the effects of two somatic-based practices, dance and martial arts, on muscle morphology (including novel USI and EI measurements), anthropometrics, and muscle function (including fatigability) in healthy older adults over a 12-week intervention period. This study's main results demonstrate that dance and martial arts interventions induce early muscular adaptation by significantly improving various aspects of muscle morphology, as measured by architectural parameters, in the vastus lateralis muscle of healthy older adults. Our results also revealed a significant deterioration in muscle architecture parameters in the control group over the same period. The findings of this study build upon and expand our previous results (Hola et al., 2024), indicating that these two somatic-based interventions not only exhibit neuroprotective effects (enhancing cognitive function and mood in older adults) but also demonstrate a protective role in age-related loss of muscle mass and quality, contributing to the growing body of evidence supporting the use of somatic practices for promoting healthy ageing (Barnstaple et al., 2021; Ciaccioni et al., 2024; Hackney et al., 2024; Hackney, 2001; Sun et al., 2024). Moreover, the efficacy of these two somatic-based practices should be considered within the broader context of a healthcare paradigm shift, where a biopsychosocial model of care is gaining traction (Omotayo et al., 2024).

6.1.1 Muscle morphology

The morphological adaptations based on architectural parameters in response to somatic-based practices in older adults have been investigated infrequently in previous research. The primary outcomes of this research reveal notable increases in the size and quality of the vastus lateralis muscle, as determined by muscle architecture and EI parameters, after a 12-week intervention period. Specifically, the martial arts group (MaG) demonstrated the most comprehensive benefits between pre-and post-intervention measurements, showing a significant 8.0% increase in MT, a 4.5% increase in FL, and a 0.9° increase in PA. The dance group (DG) also exhibited positive changes between pre-and post-intervention measurements, particularly in PA (an increase of 0.6°). When compared to the control group (CG), the change in MT was also significant. While there is no direct evidence of specific effects of dance and martial arts on VL architecture in older adults, numerous studies have consistently observed similar adaptations following active or passive resistance training programs (Ema et al., 2016; Jandova et al., 2020; Seynnes et al., 2007). An increase in muscle thickness (MT) primarily involves the addition of sarcomeres in parallel, resulting in an increased pennation angle (PA), whereas an increase in fibre length (FL), indicative of the addition of sarcomeres in series, is typically associated with eccentric exercise training involving lengthening contractions (Franchi et al., 2014). Research by Reeves et al. (2009) further elucidates the specific adaptations in muscle architecture resulting from different training modalities in older adults. In their study, both eccentric-only and conventional resistance training led to increases in FL and MT. However, only the conventional resistance training group experienced an increase in PA. This suggests that the stimulus for adding sarcomeres in series versus in parallel may differ between training types. While increased muscle size often involves the addition of sarcomeres in parallel and an increase in power output (PA), this is not a universal finding (Ema et al., 2013). In fact, the relationship between macroscopic and microscopic adaptations is complex, with Ruple et al. (2022) noting that changes in fibre CSA, FL, and PA did not collectively predict whole muscle cross-sectional area changes. These distinct architectural changes not only affect muscle size but also have significant implications for muscle function and performance. The increased PA resulting from resistance training can enhance the muscle's ability to generate force (Franchi et al., 2014), which is particularly beneficial in strength-based activities. Conversely, the increased fascicle length associated with eccentric training can enhance the muscle's capacity for rapid force production (Franchi et al., 2014) and may be advantageous in activities requiring high-speed movements or a large range of motion.

The varying degrees of muscle architecture improvements observed between the MaG and DG groups suggest that different somatic practices may elicit distinct morphological responses, which raise intriguing questions about the specific mechanisms through which each practice influences muscle architecture and hypertrophy. Factors such as movement patterns, intensity, duration, and neuromuscular engagement may contribute to these disparate results. Understanding these nuances could provide valuable insights into tailoring interventions to maximise benefits for older adults with diverse needs and capabilities. Future research should delve deeper into the underlying neuromuscular mechanisms contributing to these adaptations.

This may involve examining changes in motor unit recruitment patterns, muscle fibre type composition, and intramuscular signalling pathways associated with hypertrophy.

Although within-group reductions in echo intensity (EI) did not reach statistical significance, the between-group analysis revealed a significant decrease in EI compared to the control group, suggesting a meaningful intervention effect. This reduction in EI likely reflects a shift towards a more favourable muscle composition, with an increased proportion of contractile elements relative to non-contractile tissue (Yuan & Kim, 2023). Additionally, this improvement in muscle quality may have broader implications for metabolic health, as muscles with lower intramuscular fat content are generally linked to better insulin sensitivity and glucose regulation (Shaw et al., 2010). The observed changes in muscle quality raise intriguing questions about the underlying mechanisms and potential long-term effects. Future studies could investigate the specific cellular and molecular processes that contribute to the reduction in EI, such as changes in muscle fibre type distribution, mitochondrial density, or intramuscular lipid metabolism. Moreover, longitudinal research could examine how sustained improvements in muscle quality translate to various aspects of physical performance, including endurance, balance, and functional capacity in activities of daily living.

The observed changes in muscle architecture parameters within the control group (CG) provide compelling evidence of the early stages of muscle atrophy and potential sarcopenia development. The significant decreases in MT, PA, and FL, coupled with an increase in EI, collectively indicate a reduction in muscle size and an increase in intramuscular fat and connective tissue infiltration. These findings are particularly noteworthy given that the study participants are classified as non-sarcopenic according to USI criteria (Narici et al., 2021). This suggests that the early signs of muscle deterioration may be detectable through a detailed analysis of muscle architecture parameters before they manifest as clinically significant sarcopenia. The results of this study align with and extend upon existing literature that emphasises the rapid onset of muscle deterioration in response to physical inactivity and ageing processes (Jandova et al., 2020; Oikawa et al., 2019). The observed changes in the control group underscore the critical importance of regular physical activity in maintaining muscle health, particularly in ageing populations. These findings highlight the potential for early intervention strategies based on monitoring subtle changes in muscle architecture to prevent or delay the onset of sarcopenia. Furthermore, they emphasise the need for continued research into the mechanisms underlying age-related muscle loss and the development of targeted interventions to preserve muscle mass and function in older adults.

6.1.2 Body composition and Muscle Function

In the present study, the interventions did not result in significant changes in several body composition and muscle function parameters. This may be attributed to the moderate intensity and frequency of the training, as well as the baseline fitness and health status of the participants, which may have limited the scope for measurable improvement in the targeted muscle groups. However, the absence of significant changes in specific metrics does not necessarily indicate a lack of physiological or functional benefit. For example, numerous studies found that participation in both martial arts and dance improves cardiovascular fitness and joint flexibility. For example, a scoping review by Miller et al. (2022) demonstrated that older adults engaged in martial arts experienced improvements in aerobic endurance of up to 13.4% and flexibility gains ranging from 11.1% to over 300%, depending on the type and duration of the intervention. Similarly, a study by Wang et al. (2024) reported that older adults who engaged in dance-based aerobic exercise exhibited reductions in blood pressure and improvements in lipid profiles, thereby contributing to overall cardiovascular health. In this study, we did not measure such cardiovascular parameters, as the primary focus was on musculoskeletal outcomes; however, the nature of the interventions may have conferred additional cardiovascular benefits not captured in the current analysis. Future studies should incorporate these outcomes to understand better the full systemic benefits of movement-based interventions in older adults.

In fact, the body's adaptive responses to exercise in older adults are influenced by multiple factors, including the type, intensity, frequency, and duration of physical activity. While interventions such as martial arts and dance have demonstrated potential benefits for improving body composition and physical function in older women (Hwang & Braun, 2015; Larkey et al., 2018; Miller et al., 2022), the current evidence remains inconclusive due to methodological inconsistencies, particularly in study designs and training protocols. A study by Sanchez-Alcala et al. (2025) involving older adults demonstrated improvements in muscle strength and endurance following a 12-week dance-based aerobic training program. The rhythmic movements and weight-shifting patterns inherent in dance routines engage various muscle groups, thereby promoting muscular strength and endurance. On the other hand, martial arts, particularly striking-based styles such as kickboxing and Karate, demand repeated dynamic muscle contractions, which can help maintain and improve muscle strength. A randomised controlled trial by Lin et al. (2022) found that a 12-week kickboxing program significantly enhanced handgrip strength and gait speed in adults aged 50 to 85, indicating improvements in both muscular strength and functional mobility. In our study, we found a within-group decrease in the fatigability index following the MaG intervention, which suggests an improvement in muscular endurance. This improvement reflects a greater ability to sustain muscle contractions over time, which is clinically meaningful as it may contribute to enhanced physical function and independence in daily activities. Conversely, the significant between-group decreases in BMI, SMM, and SMI raise concerns about potential muscle mass loss in the MaG group. The slower recovery and adaptation rates of older muscle tissue, as noted by Fell and Williams (2008), suggest that the training stimulus, and perhaps also the diet, may not have been sufficient for adequate recovery and a super-compensation training response. When combined with resistance training (RT), adequate protein intake accelerates gains in muscle strength and lean body mass (Tagawa et al., 2020). These findings underscore the importance of integrating adequate nutritional support, particularly sufficient protein intake, into exercise interventions for older adults.

Improved balance and coordination are crucial for preventing falls in older adults. Dance exercise has been shown to enhance balance and reduce the risk of falls. A systematic review by Lazo Green et al. (2024) found that dance interventions, including ballroom and folk dancing, significantly improved balance and reduced the incidence of falls among older participants. Balance training is also inherently integrated into martial arts through controlled movements, stances, and weight shifts. A scoping review by Miller et al. (2022) found that martial arts, including Taekwondo and Brazilian Jiu-Jitsu, improved balance as measured by the Timed Up and Go Test and one-leg standing assessments. Given that impaired balance is a key contributor to fall risk in sarcopenia, this makes both interventions particularly relevant.

While some studies suggest that moderate-intensity exercise performed twice a week can induce measurable changes in older adults (DiFrancisco-Donoghue et al., 2007), other studies indicate that more frequent or intense training may be necessary for substantial changes (Marcos-Pardo et al., 2019). Future research should consider longer intervention periods, higher exercise intensities, or more frequent training sessions to potentially elicit more pronounced changes in body composition and muscle function parameters. Additionally, exploring the underlying mechanisms of exercise adaptation in older adults and identifying the most effective training modalities for this population remains an important area for further investigation. Together, these results underscore the intricate interplay between exercise, muscle adaptation, and nutrition in ageing populations. They also emphasize the need for comprehensive, multidimensional assessments of intervention efficacy, including strength, endurance, body composition, and functional mobility outcomes.

While the previous segment of the research (Hola et al., 2024) demonstrated neuroprotective effects, particularly in enhancing cognitive function and mood following dance intervention, the current study indicates positive outcomes on muscle morphology, specifically after martial arts intervention. Thus, the diversity of benefits observed between dance and martial arts suggests that combining these activities may offer a well-rounded approach to maintaining muscle health in older adults.

6.2 Cross-sectional data analysis of sarcopenia parameters

This study provides a cross-sectional profile of muscle function, muscle quality and body composition in a cohort of community-dwelling older females aged 65 years and above.

The observed HG (26.5 ± 5.1 kg) falls within the expected ranges for older women, with thresholds for functional decline typically cited as less than 20 kg (Cruz-Jentoft et al., 2019), indicating that most were not classified as sarcopenic at baseline. For this reason, we did not proceed with muscle mass assessment using bioelectrical impedance analysis (BIA) and the Sergi equation, as proposed by the same research group. Similarly, the MVC of 120.8 Nm compares favourably with prior studies in older females, which report average values between 100 and 130 Nm for knee extensor strength (Reid & Fielding, 2012). These findings suggest preserved force capacity, although some individuals may be near clinical cutoffs.

Despite the relatively maintained muscle mass (SMM = 25.0 kg), the high echo intensity (65.7 AU) raises concerns about the quality of the muscle. EI increases with age and is correlated with greater intramuscular fat and fibrous tissue, which compromise strength output and metabolic health (Fukumoto et al., 2012; Watanabe et al., 2013). In female populations, who generally present with higher body fat percentages, EI becomes an especially critical marker of early muscle degeneration. Given the sex-specific nature of sarcopenia, such indices may be more informative than absolute muscle mass alone.

The ultrasound sarcopenia index (USI) (4.1 ± 0.6) in this sample also supports the absence of sarcopenia, as previously introduced by Narici and colleagues. The USI offers a practical, cost-effective, and radiation-free alternative for assessing muscle mass and diagnosing sarcopenia, particularly beneficial in settings where DXA or magnetic resonance imaging are not readily accessible. Its application can aid in early detection and stratification of sarcopenia severity, facilitating timely interventions to mitigate associated risks.

The mean fat percentage (33.6%) is higher than the sarcopenia-protective ranges and may suggest a phenotype of sarcopenic obesity, particularly concerning in ageing women (Baumgartner et al., 2004). Adiposity exacerbates muscle degradation through inflammatory and metabolic pathways, even in those with preserved muscle mass. Prior studies have demonstrated that older women with elevated fat mass and low muscle quality exhibit poorer physical performance and a higher risk of frailty (Addison et al., 2014; Janssen et al., 2002). However, our group of females exceeds the widely accepted thresholds for functional independence in both gait speed and chair stand (Cruz-Jentoft et al., 2019; Manini & Clark, 2012; Studenski et al., 2011), indicating overall preserved mobility.

While this cohort of older women generally demonstrates preserved strength and mobility, markers of muscle quality, such as echo intensity and body fat percentage, suggest early signs of sarcopenia. These findings highlight the importance of incorporating ultrasound-based assessments into routine evaluations of ageing females, given their heightened susceptibility to fat infiltration and mobility loss.

The present study reveals significant correlations between muscle morphology, body composition, and physical performance, supporting and extending previous findings in the literature on musculoskeletal health, particularly in ageing and sarcopenic populations. The strong positive associations between maximal voluntary contraction (MVC) and morphological variables, such as muscle thickness (MT), fibre length (FL), and handgrip strength relative to body mass index (HG/BMI), are consistent with the mechanistic role of muscle architecture in strength generation. Similar findings have been reported by Narici and Maffulli (2010) and Morse et al. (2005), who emphasised that muscle thickness and fascicle length are key predictors of force production capacity. The inverse relationships between MVC and echo intensity (EI) and the ultrasound sarcopenia index (USI) suggest that higher intramuscular fat and connective tissue content reduce contractile efficiency, consistent with prior reports linking increased EI with decreased muscle function and quality (Fukumoto et al., 2012; Watanabe et al., 2013). These results reinforce the clinical relevance of EI as a non-invasive marker of muscle degradation.

Skeletal muscle mass (SMM) showed strong positive correlations with handgrip strength and muscle thickness, aligning with extensive literature indicating that declines in physical strength and mobility parallel reductions in muscle mass (Janssen et al., 2002; Newman et al., 2006). The negative correlation between SMM and USI provides further support for ultrasound-derived indices as effective tools for early sarcopenia screening, in agreement with Tang et al. (2022).

The observed associations between muscle thickness and both fibre length and USI confirm that larger muscle dimensions are protective against functional decline and the risk of sarcopenia. These findings align with those of Mateos-Angulo et al. (2021), who reported that muscle thickness measured via ultrasound is a reliable surrogate for muscle cross-sectional area and an indicator of functional capacity.

Handgrip strength, particularly when normalised to body mass index (HG/BMI), was positively associated with gait speed, reinforcing its status as a global biomarker of physical performance. Previous studies by Bohannon (2008) and Manini and Clark (2012) have demonstrated that grip strength strongly predicts functional independence and mortality risk across various populations.

Additionally, the deleterious role of adiposity is evident from the negative correlations between fat percentage and performance metrics (HG/BMI, chair stand test), as well as its positive correlation with EI. These associations are consistent with prior research indicating that excess fat infiltration in muscle (myosteatosis) is detrimental to muscle strength and quality (Addison et al., 2014; Goodpaster et al., 2001).

The findings of this study align well with current literature and emphasize the importance of integrating both morphological (e.g., muscle thickness, EI) and functional (e.g., handgrip strength, chair stand) assessments when evaluating muscle health and diagnosing sarcopenia. Ultrasound-based measures, such as EI and USI, offer practical, accessible, and reliable insights into muscle composition and function, particularly in clinical settings where more invasive or costly tools are unavailable. Future research should further explore longitudinal changes and the impact of targeted interventions on these interrelated parameters.

6.3 Study limitations

This study, while offering valuable insights, has limitations that warrant acknowledgement. First, the relatively small and homogeneous sample of community-dwelling older women restricts generalizability to other populations, including men or adults residing in institutions. The limitations of muscle ultrasound techniques and potential inaccuracies that may have introduced variability in the data collected were previously addressed (Jandova et al., 2020). Second, the training programs involved whole-body movements, yet we investigated muscle morphology only in the VL muscle. Synergistic or stabilising muscles engaged during training may have undergone structural or functional enhancements not captured in the study's assessments. Future research should consider a more comprehensive evaluation of muscle adaptations, including additional muscle groups, to gain a more complete understanding of the topic.

Furthermore, the issue of participant effort during maximal voluntary contractions presents a significant limitation. Variations in motivation, comprehension of instructions, or physical condition could result in submaximal performances, potentially underestimating the true extent of fatigue. Future studies could incorporate additional strategies, such as those employed by Halperin et al. (2014), or utilise electromyography (EMG) (Place et al., 2007) to more objectively assess muscle activation levels during maximal voluntary contractions, thereby enhancing the accuracy of fatigue measurement.

Furthermore, the cross-sectional design limits the ability to infer causality between muscle characteristics and functional outcomes. Additionally, the study did not assess key lifestyle factors such as physical activity, nutrition, or medication use, which may influence muscle health.

7 Conclusions and perspectives

This study highlights the intricate relationship between muscle morphology, composition, and functional performance in older adult women, offering valuable insights into effective strategies for preventing and managing sarcopenia. While the exercise interventions—dance and martial arts—did not elicit widespread changes in traditional body composition metrics, they produced meaningful improvements in muscle quality and function, particularly in muscular endurance, as evidenced by a decreased fatigability index. Martial arts, in particular, demonstrated the most comprehensive benefits across neuromuscular and functional domains.

The findings emphasise that somatically based interventions, such as dance and martial arts, offer a unique, multidimensional approach to healthy ageing. By engaging physical, cognitive, and emotional faculties, these modalities foster resilience and independence in older adults. Their dual impact on both neurological and musculoskeletal systems presents a promising framework for integrated, non-pharmacological care that addresses the multifactorial nature of age-related decline.

The study also highlights the diagnostic value of echo intensity and fatigability as emerging biomarkers of sarcopenia. These ultrasound-derived parameters offer nuanced assessments of muscle quality beyond mass alone and are particularly relevant for ageing women who face unique hormonal and physiological challenges after menopause. Given their non-invasive, portable, and cost-effective nature, tools such as ultrasound and functional performance tests (e.g., handgrip strength and gait speed) can be feasibly incorporated into routine clinical assessments, particularly in community or primary care settings with limited access to advanced imaging.

From a clinical standpoint, early detection of sarcopenia using fatigability and echo intensity enables timely and personalized interventions. These may include tailored resistance and endurance training programs optimized with nutritional strategies (e.g., adequate protein and vitamin D intake) to support muscle regeneration and reduce fat infiltration. Supervised and individualized exercise prescriptions are especially critical for older women, who benefit from structured interventions that address both physical and motivational barriers.

In conclusion, this study contributes to the growing body of evidence supporting somatic and functional movement practices as effective, culturally adaptable, and holistic approaches to healthy ageing. Dance and martial arts not only support muscle health and physical function but also contribute to psychological and social well-being—key elements of quality of life in older adulthood. Future research should aim to refine intervention protocols, explore long-term outcomes, and investigate underlying biological mechanisms to harness the preventive and therapeutic potential of these interventions fully.

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