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Multi-channel EMG manifestations of upper-extremity muscle coordination imbalance among community-dwelling sarcopenic seniors

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Abstract

Background: Sarcopenia is an age-related, insidious, crippling but curable degenerative disease if diagnosed and treated early. However, no accessible and accurate early screening method is available for community settings that does not require specialized personnel. One of the hallmarks of sarcopenia is the pathological changes of muscle fiber type composition and motor unit firing patterns. Surface electromyography (sEMG) may serve as an effective tool for detecting differences between healthy and sarcopenic individuals due to its superior wearability and accessibility compared to other screening methods such as medical imaging and bioimpedance measurements, making it ideal for community-based sarcopenic screening. Our study aims to explore sEMG biomarkers that can be used for screening or diagnosis of sarcopenia.

Results: We collected multi-channel sEMG signals from six forearm muscles of 98 healthy and 55 sarcopenic community-dwelling older adults. Participants performed grasp tasks at 20% and 50% of maximum voluntary contraction (MVC). Hexagons created by various EMG features, normalized with respect to respective MVC, and symmetry analyses were performed to estimate multi-muscle coordination patterns. An innovative index, namely incenter–circumcenter distance of muscle coordination (ICDMC), is proposed to discriminate between the healthy and sarcopenic groups. We utilized non-parametric tests to compare the ICDMC between the two groups, considering a *p*-value less than 0.05 statistically significant. The results showed that at 20% MVC, ICDMCs from root mean square (RMS), mean absolute value (MAV), slope sign changes (SSC) and wavelength (WL) showed statistically significant differences. More insights of this sEMG manifestation of sarcopenia were revealed by gender- and age-stratifications analyses.

Conclusions: Our results demonstrated that there are clear sEMG manifestations of altered muscle coordination in sarcopenic patients. More consistent force generation patterns were observed in the sarcopenic group, especially at lower contraction intensities. The novel ICDMC can quantify differences between sarcopenic and healthy muscle. These results warrant further research to further develop more accessible sarcopenia screening strategies in community settings based on electrophysiological measurements such as sEMG.

Keywords: Sarcopenia, Surface electromyogram, Diagnosis, Community-dwelling, Aging

Background

Sarcopenia is a chronic pathological condition that refers to abnormal muscle mass reduction during the aging process, in combination with weak muscle strength or poor physical performance. Studies showed that the prevalence of sarcopenia and pre-sarcopenia varies by region. In the U.S., the prevalence of sarcopenia and pre-sarcopenia is 9.6% and 47%, respectively [1], while in Asian countries, the prevalence of sarcopenia ranges from 7.3% to 12.0% [2].

Sarcopenia prominently increases the risk of falling in older adults, especially those with obesity and osteoarthritis [3]. Also, it is an important and independent risk factor for poor health outcomes including physical dysfunction, fractures, dementia, and mortality [4]. Furthermore, sarcopenia is characterized by impaired independence in activities of daily living and the bleak prognosis of chronic diseases. Many, including some healthcare professionals, believe that sarcopenia and loss of functional independence are natural and normal components of aging, so a large portion of community-dwellers remain undiagnosed [5]. It has been demonstrated that sufficient protein and energy intake, as well as regular physical exercise, can effectively prevent and treat sarcopenia. While exercise improves both function and health outcomes, early detection and prevention are critical for maximum benefit to both patients and healthcare systems [6] and contribute to less morbidity and mortality related to the disease [7]. In financial terms, sarcopenia is costly to healthcare systems and the presence of sarcopenia increases the risk of hospitalization and cost of care during hospitalization [8].

There are various classification criteria applied for the diagnosis of sarcopenia, including the European Working Group on Sarcopenia in Older People (EWGSOP) [8, 9], the Asian Working Group for Sarcopenia (AWGS) criteria [2], the International Working Group for Sarcopenia [7], and the Foundation for the National Institutes of Health [10]. For the lack of consensus or agreement for a diagnosis of sarcopenia, we are encouraged to find new diagnostic tools to complement existing methods. In current clinical practice, the diagnosis of sarcopenia is typically based on all or a combination of the following indicators: (1) low muscle mass; (2) low muscle strength; and (3) low physical performance.

Muscle mass is measured through (1) simple but ambiguous anthropometry like skinfold thickness, calf circumference, and BMI [11]; (2) credible but inaccessible imaging examinations at the community level including dual-energy X-ray absorptiometry (DEXA), computed tomography (CT) and magnetic resonance imaging (MRI); (3) portable but inaccurate bioimpedance analysis (BIA). A systematic review suggested ultrasound (US) images of the rectus femoris muscle as a promising sarcopenia diagnostic tool in multiple clinical populations [7]. However, there are no standardized protocols and clear cut-off values in clinical practice for US as sarcopenia diagnosis [12]. The latest study found that D3-creatine-estimated muscle mass may be a valuable predictor of clinical outcomes and a potential alternative to MRI for body composition assessment [13].

There is mounting evidence that muscle mass is independent of health-related outcomes and the definition of sarcopenia needs to shift from muscle mass to muscle quality.

Muscle strength is assessed by handgrip strength or lower limb strength. A quantitative measurement of lower limb strength is impossible without an isokinetic dynamometer, which is inaccessible at the community level. Handgrip strength has predictive value for assessing declines in physical and mental capacities in older adults [14]. Once power grasp strength declines to a certain extent, elderly people report increased difficulties in performing everyday tasks such as carrying heavy items, holding the handrail, and supporting themselves with a cane. Physical performance is evaluated by administering short physical performance battery score (SPPB), gait speed, and chair stand test. These tools are cross-sectional, in need of expertise, and restricted by space available. Though a recent narrative review provided an overview of currently available tools and future developments for clinical scenarios such as screening, diagnosis, and longitudinal monitoring of muscle alterations [15], it is still short of an accurate and systematic method to measure muscle mass and functional status in large cohort studies as well as in the community [16].

Many studies were exploring EMG as a new method for early detection and diagnosis of sarcopenia. EMG, as a sensitive, non-invasive, quantitative, and dynamically monitorable method, can detect subtle changes in electrical activity during muscle contraction. Elderly people diagnosed with sarcopenia usually have a loss of motor units (MUs), denervation–reinnervation process in MUs, and neuromuscular junction (NMJ) transmission failure [17, 18]. The above factors lead to electrophysiological and mechanical changes, e.g., decreased muscle strength and functional performance. Surface electromyography (sEMG) is a commonly applied technique to evaluate the physiological and morphological characteristics of skeletal muscles and their neural strategies. The abnormal electrical activity and composition of type I and II fibers can be derived by sEMG which may be sensitive to muscle changes with sarcopenia, though it is not directly reflect the single motor unit properties [19]. The current status of research is that there are now studies and articles on aging detection and sarcopenia screening. A study examined the alterations of aging back muscles by the median frequency surface electromyographic (MF-EMG) fatigue method [20]. The study found that initial MF-EMG values in the median back muscles of individuals over 50 were higher than in those under 50, though their MF-EMG fatigue slopes were less pronounced. Median frequency (MF) divides the EMG power spectrum into two equal halves and changes in MF over time indicate muscle composition. Larger muscle fibers, with higher conduction velocities, result in higher MF. Previous research observed steeper MF-EMG fatigue slopes in younger subjects, suggesting these slopes may reflect muscle aging. Researchers compared their novel IMF index with fatigue slopes using the intraclass correlation coefficient (ICC) and found IMF-EMG to be more clinically acceptable [21]. Another work demonstrated that the muscular contraction intensity (MCI) index and muscle contraction dynamics (MCD) index extracted from a high-density surface electromyogram (HDEMG) were significantly different across five age categories of healthy individuals, potentially outperforming clinical and DEXA parameters in accessing muscle aging [22]. These studies demonstrate the potential of using EMG to evaluate sarcopenia in community or home settings. With the combination of appropriate signal processing

techniques and models, along with the development of portable and wireless sensors, it is expected to become an important approach to sarcopenia diagnosis in the future.

In this study, through a cohort of community-dwelling senior participants, we investigated if upper limb multi-channel sEMG patterns provide discriminative information for sarcopenia and if such information can be used for community-based diagnosis of sarcopenia. We hypothesized that multi-channel patterns differ between the sarcopenic and healthy groups, and that these differences are associated with muscle strength and skeletal muscle mass.

Results

Level 1: comparison between the sarcopenia and the healthy group

Age, calf circumference, height, weight, handgrip strength, and SMI all exhibited significant differences between the healthy and the sarcopenia group ($p < 10–3$), except for the duration of the 5-STS test (see Table 1). The handgrip strength test of the sarcopenic group (SG) showed a greater decline in upper-extremity strength than the 5-STS test, suggesting the upper-body strength of sarcopenia patients declined more than lower-body strength. As observed from the violin plots, time-domain features exhibited a distribution where the median ICDMC values were lower in the SG compared to the healthy group (HG), and the distribution in the SG was more concentrated than that in the HG. A lower ICDMC median indicated that electromyographic activity and muscle contractions are more consistent among sarcopenic patients. The ICDMCs from RMS ($p = 0.006$), MAV ($p = 0.004$), SSC ($p = 0.002$), and WL ($p = 0.013$) at 20% MVC were significantly different between the two groups (Fig. 1). This result suggested that these sEMG features provided discriminative information between sarcopenic and healthy elderly individuals. However, no statistical difference was found at the 50% MVC. The sEMG features obtained under low effort levels offer practical advantages, as they are convenient for daily monitoring and do not cause injuries, pains, or fatigue in elderly individuals. It is likely that confounding factors, such as differences in gender and age between the two groups, prevent us from confirming that the significant differences observed at 20% MVC solely originate from a diagnosis of sarcopenia. Therefore, additional comparisons were conducted.

Table 1 Characteristics of participants

Variable	Sarcopenia group Mean ± SD	Healthy group Mean ± SD	*P*-value
N	55	98	
Age	75.1 ± 7.4	70.7 ± 7.1	< 0.001
BMI (kg/m^2)	22.1 ± 2.6	23.6 ± 10.3	< 0.001
Calf circumference L (cm)	31.0 ± 2.1	33.7 ± 8.9	< 0.001
Calf circumference R (cm)	31.3 ± 2.4	33.9 ± 9.4	< 0.001
Height (cm)	151.9 ± 9.1	157.9 ± 8.0	< 0.001
Weight (kg)	51.1 ± 8.3	59.1 ± 10.5	< 0.001
Handgrip strength (kg)	18.0 ± 5.2	23.9 ± 7.0	< 0.001
5-STS (s)	10.7 ± 5.3	10.6 ± 3.1	0.406
SMI (kg/m^2)	5.6 ± 0.7	6.4 ± 0.9	< 0.001

BMI, body mass index; SMI, skeletal muscle mass index; SD, standard deviation; M, male; F, female

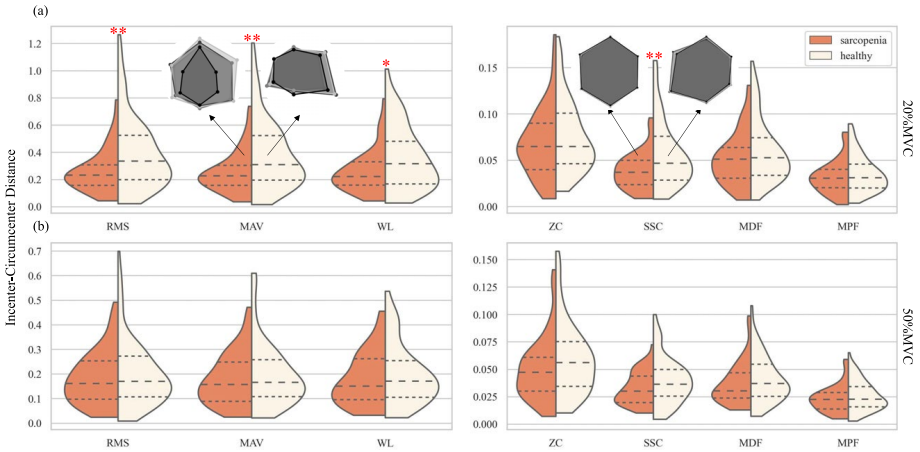

Fig. 1 Comparison between the sarcopenia and the healthy group. (**a**): the spider plots on either side of the MAV and SSC represent the subjects from the sarcopenia group and the healthy group at the corresponding contraction level (left-sarcopenia, right-healthy). Representative example of the hexagons was given for both groups of MAV and SSC. It can be intuitively observed that the hexagons (4 trials) for the sarcopenia participants are more symmetric than healthy participants, reflected by the smaller median ICDMC for the sarcopenia group

Table 2 Characteristics of participants, stratified by gender ($n = 153$)

	Male group Mean ± SD		Female group Mean ± SD		P-value	
	Sarcopenia group	Healthy group	Sarcopenia group	Healthy group	Male	Female
N	19	30	36	68		
Age (years)	78.4 ± 6.4	72.3 ± 6.7	73.3 ± 7.4	69.9 ± 7.2	0.003	0.026
BMI (kg/m^2)	22.4 ± 2.0	23.9 ± 3.4	22.0 ± 2.8	23.5 ± 3.2	0.049	0.018
Calf circumference L (cm)	32.6 ± 1.6	34.1 ± 2.8	30.2 ± 1.8	33.5 ± 2.8	0.012	< 0.001
Calf circumference R (cm)	32.6 ± 2.3	34.3 ± 2.8	30.3 ± 1.8	33.3 ± 2.6	0.008	< 0.001
Height (cm)	160.3 ± 6.0	165.4 ± 7.4	147.4 ± 7.0	154.6 ± 5.7	0.015	< 0.001
Weight (kg)	57.4 ± 5.7	64.2 ± 9.5	47.0 ± 5.4	56.3 ± 8.4	0.004	< 0.001
Handgrip strength (kg)	24.1 ± 2.9	32.1 ± 5.3	14.8 ± 2.6	20.4 ± 3.6	< 0.001	< 0.001
5-STS (s)	9.6 ± 3.8	9.9 ± 2.3	10.6 ± 4.4	10.9 ± 3.0	0.951	0.224
SMI (kg/m^2)	6.5 ± 0.3	7.2 ± 0.9	5.2 ± 0.3	6.0 ± 0.7	< 0.001	< 0.001

BMI, body mass index; SMI, skeletal muscle mass index; SD, standard deviation; STS, sit-to-stand; M, male; F, female

Level 2: comparison stratified by gender

During the experimental sessions, we observed some differences in EMG patterns between the two genders, so we conducted stratified analyses by gender. Other than 5-STS, all other indicators exhibited significant differences between the two groups. It should be noted that the age of male SG was 78.4 ± 6.4 years, and the HG was 72.3 ± 6.7 years; the age of female SG was 73.3 ± 7.4 years, and the HG was 69.9 ± 7.2 years. The indicators (BMI, calf circumference, and weight) reflecting weight status showed fewer differences in males compared to females, yet the male group was notably older than the female group (see in Table 2). These were confounding factors for ICDMC group differences among EMG features. In EMG feature analysis, only the male

ICDMC from WL ($p=0.001$) at 20% MVC contraction level showed a significant difference between the groups. However, in the females, the ICDMCs from RMS ($p=0.02$), MAV ($p=0.013$), SSC ($p=0.007$) at 20% MVC contraction level, and MDF ($p=0.044$) at 50% MVC contraction level showed statistical differences (Fig. 2). This suggested that there is a gender-specific difference in the sarcopenia-related EMG features. Additionally, the SG was older than the HG, consistent with EMG findings, where age-related changes in EMG features, particularly frequency-related features like WL and SSC, were more pronounced. Differences reflected in RMS and MAV indicated closer links with body composition and muscle strength.

Level 3: comparison stratified by age

To control the confounding effect of age on EMG, we further stratified the samples by age for comparison. Handgrip strength ($p<0.001$) and SMI ($p<0.001$) showed significant differences between the sarcopenia and the healthy groups in the 60–69 and 70–79 age groups, respectively, but not in the 80+group. This aligned with the EMG analysis results that ICDs from RMS and MAV at 20% MVC exhibited statistical differences between the groups in the 60–79 and 70–79 age ranges but disappeared in 80+group (Fig. 3a, b). This suggests a correlation between ICDs and SMI. The 5-STS had no differences in the first two age groups but showed statistical differences in the 80+group. In the 80+group, ICD from ZC ($p=0.002$) and SSC ($p=0.032$) at 50% MVC contraction level showed significant differences between the groups (Fig. 3c). However, these results may be less reliable because handgrip strength and 5-STS average duration were better in the SG, which contradicts common sense. This discrepancy likely arises from an imbalanced composition of males and females. The sarcopenia group consists of 11

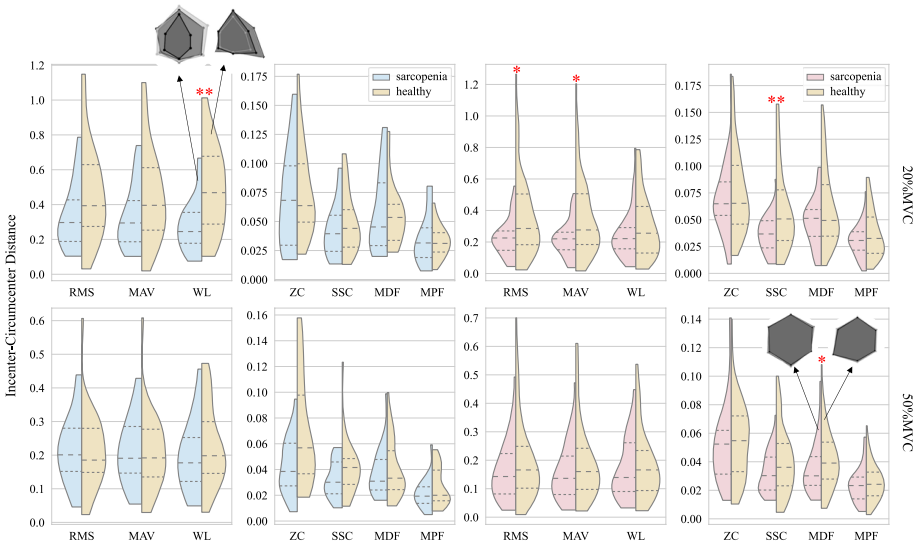

Fig. 2 Comparison between the sarcopenia and the healthy group, stratified by gender. The ICDMC acquired from different EMG features presented disparity between the genders. The blue plots represent results from males, and the pink plots represent results from females. The ICDMCs demonstrated discriminative ability for sarcopenia in different ways, which could be due to age and muscle strength differences between genders. Abbreviation: sar, sarcopenia subject; hea, healthy subject; RMS, root mean square; MDF, median frequency; WL, wavelength

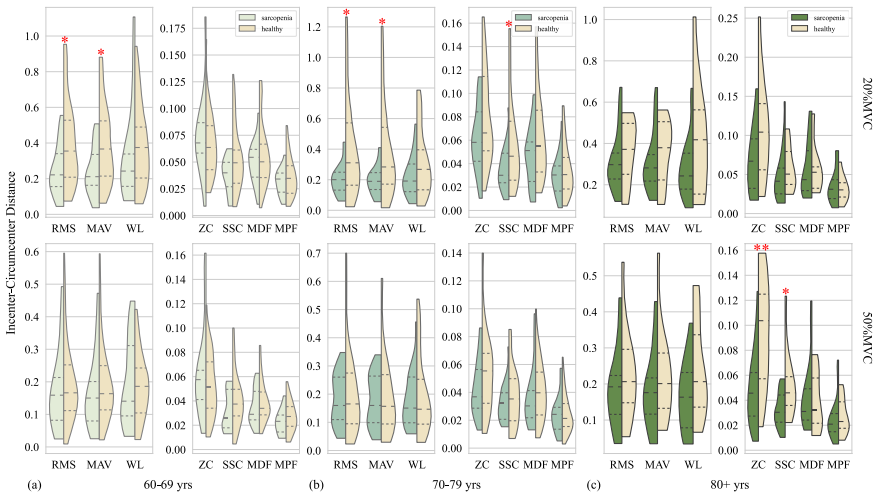

Fig. 3 Comparison between the sarcopenia and the healthy group, stratified by age

males and 9 females, whereas the healthy group consists of 4 males and 8 females. The small sample size of males in the healthy group lead to a lower handgrip strength.

Discussion

The purpose of this study was to identify sEMG manifestation of sarcopenia for early screening and diagnosis of the condition from multi-channel sEMG patterns and to investigate the relationship between ICDMCs and SMI. The main findings are: (1) ICDMCs extracted through RMS, MAV, SSC, and WL at a low contraction level, rather than higher effort levels, contained discriminative information between sarcopenic patients and age-matched healthy controls (Fig. 1); (2) there was a noticeable alteration in the spatial distribution of EMG activities in sarcopenia patients, with more consistent and stable multi-channel patterns across varying contraction levels compared to healthy controls during the grasp task; (3) sex differences had impact on ICDMCs from which EMG features could be applied in early screening and diagnosis of sarcopenia (Fig. 2). These results support parts of our hypothesis that sarcopenic patients exhibit changes in multi-channel sEMG patterns. Specifically, the results of smaller ICDMC values of sarcopenic patients indicated more consistent muscular coordination across different contraction levels, which is contrary to our original assumption. Given the decline in muscle strength and performance in older adults with sarcopenia, we originally hypothesized that the healthy group (HG) would have smaller values of ICDMC, indicating a more symmetric hexagon.

One interpretation of this unexpected finding is the age-related change at the muscle fiber level. Extensive histological results have shown that in animal models of sarcopenia, there is a decrease in the percentage of type II and a preservation of type I muscle fibers. Different types of muscle fibers possess distinct electrical and mechanical properties and bear different tensions at various contraction levels [23]. The relatively more consistent EMG pattern in sarcopenic patients at various contraction levels could be due to the predominance of type I fibers in the muscles, and fiber compositions across

muscles become more uniform, resulting in more symmetric EMG pattern, and consequently in a smaller measured ICDMC [24].

Another possible mechanism is the change in discharge characteristics of sarcopenia muscles. Existing studies, both in animal experiments and human trials, have shown that the discharge rate of the MU decreases at maximal contraction in people diagnosed with sarcopenia [25]. When the discharge rate decreases, the recruitment probability of high-threshold MUs declines. Further, a significant loss of type II in the sarcopenia leads to a loss of MU innervation [26], and the denervated MU may be remodeled by nearby low-threshold motor neurons. As such, the ability to activate MUs normally is impaired for sarcopenic individuals. In these cases, when normalized by the EMG features from the participant's own MVC, multi-channels represented more similarities and less inter-channel variability in people diagnosed with sarcopenia because lower effort recruits fewer type II muscle fibers.

Our results suggested that sEMG has the potential to diagnose sarcopenia supported by more evidence. Hirono et al. used the HDEMG method to study the firing rate of vastus lateralis (VL) between healthy and pre-sarcopenic older adults from Japan. They observed that high-recruitment threshold MUs in pre-sarcopenia fire with a strategy commonly found in high-intensity contraction or even MVC to increase the rate even during middle-intensity contraction, such as 50% of MVC [27]. Thus, with disease progression, we can infer that sarcopenic patients employ this strategy at a lower contraction level, and the firing pattern corresponds to MVC. Consequently, the sarcopenia group shows more regular hexagons when normalized to MVC, resulting in electrical activity more similar to MVC. If this inference really happens to those with sarcopenia, this study supports our results of a more similar EMG activity patterns, more symmetrical hexagon and smaller ICDMC at a low contraction level. In another study, Piasecki et al. examined the differences in motor unit action potentials (MUAPs) among young, non-sarcopenic, pre-sarcopenic, and sarcopenic men. They found that MUAPs were significantly smaller in sarcopenic compared with pre-sarcopenic men. They also observed that both non-sarcopenic and pre-sarcopenic men had significantly larger MUAPs than younger men. Smaller MUAPs indicate either the muscle units have fewer muscle fibers or impaired muscular contraction function [28]. This study was the first to directly compare the number and size of MUs to assess patients with different sarcopenic states. It provided solid evidence for the alteration of MU as the progression of disease. The commonality of the above two studies is that compensatory mechanisms can be observed in the pre-sarcopenic state, but disappear once sarcopenia progresses, highlighting the importance of early screening, diagnosis, and intervention.

A recent work about sarcopenic dysphagia found that the muscle activity duration was longer, and the amplitude was higher [29]. Similar phenomena were observed when we inspected raw EMG signals acquired in the current study. Although we did not directly measure the skinfold thickness, the records of weight, BMI and SMI could indirectly reflect the body fat percentage of the participants. The elderly people with low SMI and BMI were quite thin. These findings suggest that EMG signal amplitude is more influenced by subcutaneous tissue and fat thickness than by the contraction level. The significance of this conclusion was that indices, or features extracted from EMG can be a clinical alternative to SMI as a diagnostic parameter. The thinner the tissue, the higher

the EMG signal amplitude, indicating that some features calculated directly from the amplitude lack robustness. Time–frequency features, such as RMS and MAV, are entirely derived from amplitude, whereas SSC and WL not only correlate with amplitude but also reflect frequency-related information. Frequency-domain features MDF and MPF showed hexagons very similar to regular ones, regardless of contraction levels, making it difficult to distinguish between healthy and sarcopenic individuals. However, they often demonstrate potential applications in aging and fatigue monitoring via EMG [21]. These metrics, including ICDMC may be valuable for diagnosing sarcopenia if we properly select multidimensional parameters to build prediction models. Certainly, we must continue to expand our database.

Intramuscular electromyogram (iEMG) and sEMG techniques were simultaneously applied to participants of different age groups [30, 31]. Key findings emerged that MUAPs amplitude/area/turns could identify and differentiate muscle aging. However, iEMG is an invasive and pain-producing operation, which likely would have compliance issues in community-dwelling elderly.

Our rationale for extracting suitable sEMG manifestations is due to the fact that EMG signals reflect physiological information, neuromuscular alterations, and muscle function. Hu et al. demonstrated that an EMG could differentiate muscle types, such as the proportion of type 1 vs. type 2 muscle fiber pattern types of MU recruitment, but few studies have used SEMG decomposition techniques for the diagnosis of sarcopenia [32]. Many literatures focused on the assessment of muscle mass and structural information using different means, though as mentioned in this study, muscle mass is not the only determinant of muscle strength. Still, other factors such as muscle relaxation and muscle fiber atrophy can also explain low muscle strength [33]. Many studies claimed that the loss of muscle mass was induced by an age-related decline in muscle fiber number and size. However, this article revealed an important phenomenon that neural alterations proceeded with reductions in peripheral muscle substance. This controversy calls for further research to explain the primary and secondary relationship between central and peripheral degeneration in sarcopenia. We were surprised to find that some teams [34, 35] are already trying to build a system for early screening and diagnosis of sarcopenia based on sEMG. Despite being in the early stage of research, our team has been motivated to do further studies.

This current research has made some contributions to the literature. First, it provides new evidence and data to the existing studies of early detection and diagnosis of sarcopenia via sEMG. Previous literature research has shown that although EMG is used broadly in clinical practice, there are more than ten articles that directly apply it to sarcopenia, many of which have only investigated the disparity in EMG signals associated with aging. More importantly, the sample size of these studies was all small and had limited data from older participants, especially those diagnosed with sarcopenia. The elderly may be more vulnerable to day-to-day fluctuations in physical and mental health, making it necessary to explore and study this population separately. In the current study, the data collection process lasted for several months, covering four different communities. We completed the collection of EMG data of 60 sarcopenic seniors and more than 100 healthy elderly people. To our knowledge, this is the largest EMG study on sarcopenia to date.

Second, other studies mainly observed lower extremity muscles including quadriceps, hamstrings, tibialis anterior, and triceps surae, and there are also researches monitoring trunk muscle groups like dorsal extensors and swallowing muscles. As a nondistinctive functional decline and muscular disorder of the entire body, the present study complements the lack of investigation into upper limb muscles. It is widely recognized that upper limb muscle function plays an important role in daily activities, and from the results of this study, the handgrip strength showed a significant difference between groups when the lower limb functional test did not (Table 1). This may denote that the impact of aging and sarcopenia on upper limb muscles is more pronounced and rapid.

Last but not least, we proposed the graphical representation of normalized EMG features combined with symmetry analysis. The final index ICDMC can reflect the synergistic force generation of the muscles considering six-channel EMG energy spatial distribution from a macroscopic aspect. We add the EMG acquisition during individual maximum voluntary grasp to our protocol to reduce the interference of individual grip strength on the EMG features since time-domain features reflecting the energy information (especially RMS/IEMG/MAV) have a positive relation with muscle force. The common patterns presented for men and women were: (1) time-domain features showed a statistical difference between groups at low-intensity contraction, whereas frequency-domain features were homogeneous across channels irrespective of disease and contraction level; (2) the correlation between EMG features and muscle contraction intensity was weaker in sarcopenia; and (3) the variability of data was greater in healthy controls.

There are several limitations of the current study. First, there exists sample imbalance in this study, with the sarcopenia group having half the sample size of the healthy group, and the male being half the number of the female. The first reason for gender-imbalance is that females are in general more likely to actively participate in social activities and new experiences compared to males of similar age [36]. Secondly, our female participants usually demonstrated more patience and compliance than male participants. As such, we did not intentionally select participants to achieve equal sample sized between genders. Our experiments were conducted in a natural population with a prevalence of sarcopenia merely 10%. Consequently, the only way to expand illness recruitment is to multiply the screening populations, which requires more resources. Nevertheless, this is an ongoing research initiative, and we will expand the size of our database. From a clinical perspective, our team will collect more detailed information about the participants, including chronic disease, physical activity levels, and nutritional status. From an engineering perspective, we will try traditional geometric symmetry analysis metrics, employ machine learning and deep learning models to enhance classification accuracy, and validate the effectiveness of these models across both new and existing datasets.

Secondly, this study lacks reproducibility testing and is only a cross-sectional study which only provides a snapshot in time, making it difficult to determine the direction of causality between variables and assess changes over time. Meanwhile, in cross-sectional studies, participants range in age from 60 to over 90, potentially masking variations in EMG. Additionally, MU firing patterns and muscle structures change with aging, particularly in individuals over 80 years old, whose EMG activity differs significantly from those in the 60–79 age group [37]. After the expansion of the sample size, we can develop more exquisite models by age stratifications. Additionally, we can conduct

annual follow-ups on participants within the database and observe the longitudinal changes of the extract sEMG index.

Finally, the handgrip dynamometer we used was unable to record data, so the force data were missing. If grip strength data were available, we could analyze and compare the fluctuation of strength in healthy and sarcopenic older adults, demonstrating a decrease in the MU discharging rate [38]. Our team is developing a handgrip dynamometer integrated with EMG sensors, capable of concurrently recording force and EMG data with high consistency. This system will enhance the precision of EMG segmentation and enable a comprehensive analysis of force patterns in sarcopenic versus healthy elderly individuals using multimodal data.

Conclusion

The present study provides new evidence of altered multi-channel patterns in a group of community-dwelling older adults. A new index, ICDMC, derived from time-domain features, was significantly smaller in the sarcopenic group during low-effort grasping. Sarcopenia alters upper limb muscle coordination, reducing variability across different contraction levels. This is likely caused by changes in mechanical properties, where the composition of type I and II muscle fibers becomes dominated by one type. Consequently, the control from the central nervous system and the electrophysiological activities recorded by sEMG change. Our findings suggest the potential of sEMG as an early screening, monitoring, and diagnostic tool for sarcopenia at the community level; this hypothesis should be explicitly tested and validated in future studies.

Methods

Participants

Community-dwelling seniors were recruited from four normal mixed-generation communities to participate in this study. The inclusion criteria were: (1) > 60 years of age and had independent ambulation; (2) generally healthy, free of osteoarthritis of upper extremities especially hands; (3) no cognitive impairment, optical dysopia, or hearing loss that would interfere with testing; (4) free from any functional limitations; and (5) independent in their activities of daily life (ADL). The exclusion criteria were: (1) unable to follow instructions given in Mandarin; (2) had metal implants, including pacemakers, artificial hip joints, heart stents, dentures, etc.; (3) had surgery on both hands or wrists within the last three months; (4) had prosthetic hands or legs; (5) was unable to stand or rise unaided; or (6) with severe leg trauma. A total of 153 participants were recruited, aged 60–91 years old (49 male and 104 female). The experimental protocol was approved by the Institutional Research Board of West China Hospital Sichuan University (WCHSCU_2023_317). All participants provided informed consent and were compensated commensurably for their time and participation.

Methodology

Basic information was obtained by inquiries, including age, gender, and education. Meanwhile, the investigators also asked participants about primary diseases, medical history, and medications. In addition, they confirmed whether the participants had metal implants or pain in their hands, wrists, or elbows.

Conventional measurement and sarcopenia diagnosis

Body composition was determined using segmental multifrequency Bioelectrical Impedance Analysis (BIA; Inbody 770, Biospace Co. Ltd., Seoul, Korea). This device measures the impedance of the trunk and extremities and calculates the value of skeletal muscle mass index (SMI) by proprietary algorithms considering factors such as the individual's height, weight, age, and gender. The calf circumference measurement is commonly used to indicate muscle loss or frailty in the lower leg. For this measurement, the participants remained seated and rolled up their pants legs with lower legs perpendicular to the ground and knees flexed at 90 degrees. The investigator used a sewing tape and measured the thickest part of the calf, typically at the midpoint between the knee and ankle. Next, the participants who could stand up without aid were allowed to complete the sit-to-stand test. The participants started in the sitting position in a chair, folding their hands across the chest, and tried to rise to the standing position as quickly as possible from the chair. The participant repeated this task five times and the total duration was recorded. The handgrip strength was measured using a SENSSUN EH101 dynamometer. The dynamometer handle width was adjusted for the individual participant so he/she could perform the handgrip test comfortably. The participant was in a standing position, arms down by the side, and performed three trials only for the dominant hand; the best trial was included in the analysis.

From these measurements, the diagnosis of sarcopenia was performed based on the Asian Working Group for Sarcopenia: 2019 Consensus Update on Sarcopenia Diagnosis and Treatment [2] as illustrated in Fig. 4. The participants were diagnosed as sarcopenia by either low handgrip strength or poor performance in the chair stand test in combination with low skeletal muscle mass index. According to the assessment results, 55 participants were diagnosed with sarcopenia, including 9 with severe sarcopenia. The remaining 98 individuals were classified as healthy (Table 2).

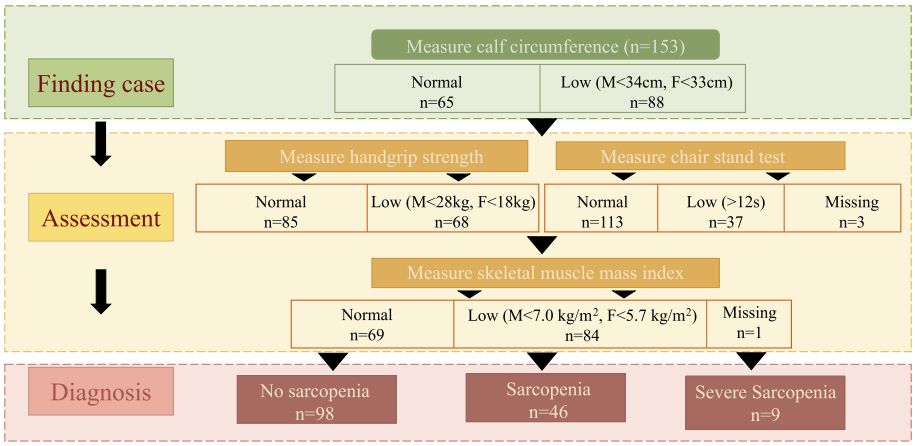

Fig. 4 Flowchart when applying the AWGS2019 algorithm on 153 community-dwelling seniors 60 years and older living in Chengdu City, Sichuan Province, China. Community-dwelling elderly individuals with calf circumference below the standard (males <34 cm, females <33 cm) may be potential cases. Subsequently, assessments were conducted in terms of muscle strength, physical performance, and muscle mass. The participants were diagnosed as sarcopenia by either low handgrip strength or poor performance in the chair stand test in combination with low skeletal muscle mass index. When all three tests indicate a deficit, the participants are diagnosed with severe sarcopenia. Abbreviation: AWGS2019, Asian Working Group for Sarcopenia: 2019 Consensus Update on Sarcopenia Diagnosis and Treatment. M, male. F, female

Surface EMG acquisition procedure

Electromyographic signals were acquired using wireless surface electromyography with inertial measurement units (Ultium EMG, Noraxon, USA). All participants were asked about their handedness before the experiment began and only recorded one side of the forearm's EMG signal. In this experiment, we applied electrodes with a diameter of 30x24mm (31.1245.21, Kendall, Cardinal Health 200, LLC) for data acquisition. After the skin had been abraded with alcohol, 12 electrodes were attached to 6 different muscles of the forearm in parallel with the direction of muscle fiber, which are brachioradialis (BRA), flexor carpi ulnaris (FCU), flexor carpi radialis (FCR), extensor carpi ulnaris (ECU), flexor digitorum superficialis (FDS), extensor digitorum (ED). All sensors were attached to the skin (Table 3) with a double-sided adhesive interface, by investigators who were well-trained in administering the sensors.

During the experiment, the participant was seated in a comfortable chair, holding the dynamometer in hand, and hanging naturally at the side of the body as shown in Fig. 5. There was a table in front of the participant for the test laptop, facing the participant. The experimenter stood at the dominant hand side of the participant, making sure the participant saw real-time readings of the grip dynamometer, displayed on the laptop screen. After the preparation, each participant completed the following tasks.

Trial one (T1): the experimenter recorded a 10-s resting state's EMG signal as the baseline data, and then encouraged the participant to grasp the dynamometer for the maximal voluntary contraction (MVC) for at least 3 s. Each participant repeated the MVC contraction three times, with the necessary rest time between these MVC contractions. Trial two–five (T2–T5): during these contraction trials, the EMG recording began 10 s before the actual griping task and continued for 10 s after the task was completed. In the T2 trial, participants were instructed to perform 20% and 50% MVC contractions in a random order, each for ten seconds [39, 40]. From our pilot study (involving approximately 20 elderly people), we found it challenging for elderly participants to achieve the lower contraction level goal with 5% error margin. Additionally, contraction strategies and patterns were similar at lower contraction levels ranging from 10 to 30% MVC. A trial was considered successful if the participant maintained the contraction within a 10% error margin for the full 10 s. A rest period was provided before T3, during which the investigator reversed the order of

Table 3 Electrode location method

Which muscle?	Which side?	Electrode placement
Brachioradialis (BRA)	Lateral	Upper 1/4 of the line from the lateral epicondyle to the styloid process of the radius
Flexor carpi radialis (FCR)	Palmar	Upper 1/3 of the line from the medial epicondyle to the styloid process of the radius
Flexor digitorum superficialis (FDS)	Palmar	1/2 of the line from the medial epicondyle to the midpoint of the distal wrist crease
Flexor carpi ulnaris (FCU)	Medial	Upper 1/3 of the line from the medial epicondyle to the styloid process of the ulnar
Extensor carpi ulnaris (ECU)	Dorsal	Upper 1/3 of the line from the lateral epicondyle to the styloid process of the ulnar
Extensor digitorum (ED)	Dorsal	1/2 of the line from the lateral epicondyle to the midpoint of the distal wrist crease

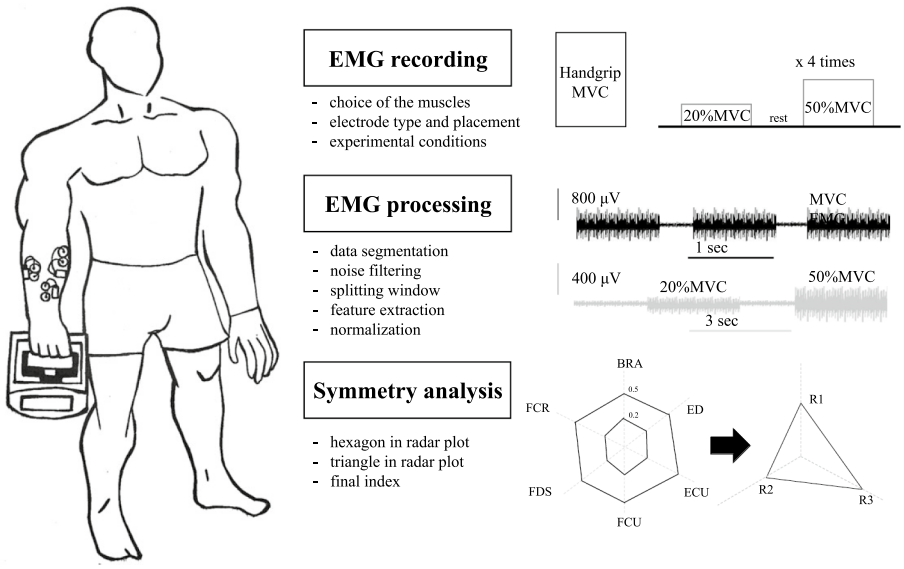

Fig. 5 Experimental protocol and EMG processing pipeline. EMG recordings were obtained during three trials of maximal grip strength and four trials of two different submaximal grasp levels. Subsequently, EMG signal segments with a stable amplitude were extracted for further processing and analysis. Abbreviation: MVC, maximal voluntary contraction. 1 sec, 1 second. 3 sec, 3 seconds

Table 4 Feature extraction formulae

$$RMS = \sqrt{\frac{1}{N}\sum_{i=1}^{N} x_i^2} \quad (1)$$

$$IEMG = \sum_{i=1}^{N} |X_i| \quad (2)$$

$$MAV = \frac{1}{N}\sum_{i=1}^{N} |x_i| \quad (3)$$

$$WL = \sum_{N}^{N-1} |X_{i+1} - X_i| \quad (4)$$

$$ZC = \sum_{i=1}^{N-1} \left[sgn(x_i \times x_{i+1}) \cap |x_i - x_{i+1}| \geq threshold \right] \quad (5)$$

$$sgn(x) = \begin{cases} 1, & otherwise \\ 0, & x \geq threshold \end{cases}$$

$$SSC = \sum_{i=2}^{N-1} \left[f\left[(x_i - x_{i+1}) \times (x_i - x_{i+1}) \right] \right] \quad (6)$$

$$f(x) = \begin{cases} 1, & otherwise \\ 0, & ifx \geq threshold \end{cases}$$

$$MNF = \sum_{j-1}^{M} f_j P_j \Big/ \sum_{j-1}^{M} P_j \quad (7)$$

$$\sum_{j=1}^{MDF} P_j = \sum_{j=MDF}^{M} P_j = \frac{1}{2}\sum_{j=2}^{M} P_j \quad (8)$$

contraction levels compared to T2. T4 and T5 were repetitions of T2 and T3. The trials were repeated four times with randomization to eliminate bias and enhance reliability. This approach balanced the limited experimental time in community settings

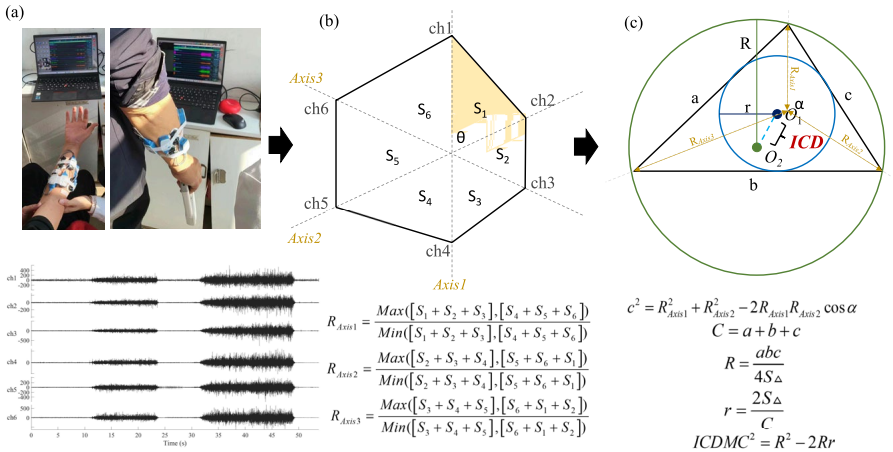

Fig. 6 Symmetry analysis flowchart. The area of the yellow triangle was calculated using normalized feature values from channel 1 (ch1) and channel 2 (ch2) for an angle θ of 60°. For an angle α of 120°, the sides of the triangle (**a, b, c**) and area were determined. The circumference (C), circumradius (R), inradius (r) of the triangle, and the final indicator (ICD) were then calculated

and scientific requirements of the research. All participants were able to perform the tasks correctly following the instructions.

EMG signal analysis

The sEMG data recorded with Ultium EMG (Noraxon, USA) were imported to PyCharm (PyCharm Community Edition 2022.1.3, JetBrains, Czech Republic). All raw EMG signals were notched filter at 50 Hz and a third-order bandpass filter between 20 and 500 Hz [41]. An sEMG expert visually inspected all EMG signals and extracted one-second epoch of the MVC EMG with a stable amplitude from T1, as well as three-second epochs, with a steady force segment from 20% or 50% MVC trials of T2–T5.

For each extracted epoch, a 200-ms segment of EMG was further extracted with a step-size of 50 ms from which the sEMG features were calculated and the features extracted from each averaged segment. The feature sets include time-domain features: root mean square (RMS), mean absolute value (MAV), zero crossing (ZC), integrated electromyography (IEMG), slope sign changes (SSC), and wavelength (WL); frequency-domain features: mean power frequency (MPF), median frequency (MDF) [42]. Table 4 shows the mathematical equation of each introduced feature [42]. All features were extracted by using Python. Before further analysis, the average feature values from MVC trials were used to normalize the feature values obtained in other trials.

Spider plots were created with the normalized feature values from the six EMG channels. There was one hexagon for each trial, with eight features and two contraction levels. The feature value of each channel was the radial length of one spoke of the hexagon in Fig. 6. The hexagon for the MVC contraction was a regular symmetric hexagon with six unit-length spokes. If the EMG activations of the six channels at 20% and 50% MVC contractions were proportional to those of the MVC contractions, the resulting hexagon was symmetric, with spokes at reduced lengths (not necessarily at 0.2 and 0.5, respectively). On the other hand, if the EMG activations of the six channels in the 20% and 50% were not proportionally changed with respect to their MVC counterparts, the resulting

hexagon was asymmetric. The area of each triangle filled in yellow in Fig. 6b was calculated by formula and the area of one side of the symmetry axis is the sum of areas of three triangles. To quantify the degree of asymmetry, the ratio of area on both sides of the symmetry axis was calculated according to the ratio between the larger side divided by the smaller side. In this manner, each Spider plot was produced in three ratios, namely R_{Axis1}, R_{Axis2}, and R_{Axis3}, from which a triangle was obtained as shown in Fig. 6c. Using the cosine theorem, the lengths of the triangle's sides were calculated. Subsequently, the perimeter of the triangle (C), the area of the triangle ($S_{\triangle}$), the radius of the incircle (r), and the circumcircle (R) of the triangle were determined. Finally, the incenter–circumcenter distance of muscle coordination (ICDMC) was computed using Euler's formula, serving as the asymmetry index. A smaller ICDMC value indicates greater symmetry of the hexagon, with a zero ICDMC indicating a perfectly symmetric hexagon. In the final statistical analysis, the trials averaged, so each subject has a hexagon for each contraction level and each feature.

Statistical analysis

First, group-level comparisons were performed between the healthy group and the sarcopenia group. Subsequently, the data were stratified by gender (male, female) and age for further comparison to identify differences in various metrics between the healthy and disease groups. It has been demonstrated that sex differences exist in neural drive, motor unit (MU) firing behavior, force output, and hormone levels [43–45]. Therefore, it is essential to explore the EMG differences stratified by gender. Additionally, MU firing patterns and muscle structures change with aging, particularly in individuals over 80 years old, whose EMG activity differs significantly from those in the 60–79 age group [37] .

All data, including categorical variables such as the diagnosis of sarcopenia and gender, and continuous variables such as age, calf circumference, height, weight, handgrip strength, duration of the 5-time sit-to-stand test (5-STS), SMI, BMI, and final indicators from sEMG, were entered into IBM SPSS Statistics 23. The final indicator, ICDMC, for each feature at different contraction levels, was calculated for both study groups. The Kolmogorov–Smirnov test and Shapiro–Wilk test were used to examine the dataset's normality. Outliers were checked and replaced with the mean or median based on the data distribution. For variables following a normal distribution, an unpaired *t*-test was used to compare group means, with a *p*-value less than 0.05 considered statistically significant. For non-parametric variables, the Mann–Whitney *U*-test was used for group comparisons.

Abbreviations

sEMG	Surface electromyogram
MVC	Maximum voluntary contraction
ICDMC	Incenter–circumcenter distance of muscle coordination
BMI	Body mass index
EWGSOP	European Working Group on Sarcopenia in Older People
AWGS	Asian Working Group for Sarcopenia
DEXA	Dual-energy X-ray absorptiometry
CT	Computed tomography
MRI	Magnetic resonance imaging
BIA	Bioelectrical impedance analysis
US	Ultrasound

SPPB	Short physical performance battery score
MUs	Motor units
NMJ	Neuromuscular junction
HDEMG	High-density surface electromyogram
ADL	Activities of daily life
SMI	Skeletal muscle mass index
BRA	Brachioradialis
FCR	Flexor carpi radialis
FDS	Flexor digitorum superficialis
FCU	Flexor carpi ulnaris
ECU	Extensor carpi ulnaris
ED	Extensor digitorum
RMS	Root mean square
MAV	Mean absolute value
ZC	Zero crossing
IEMG	Integrated electromyogram
SSC	Slope sign changes
WL	Wavelength
MPF	Mean power frequency
MDF	Median frequency
5-STS	5-Time sit-to-stand test
SG	Sarcopenic group
HG	Healthy group
VL	Vastus lateralis
MUAPs	Motor unit action potentials
iEMG	Intramuscular electromyogram

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Author contributions
Conceptualization: HRH, JYH, and NJ; methodology: HRH, NL, XCW, YJ, JYH and NJ; formal analysis and investigation: HRH, XCW, JYH and NJ; writing—original draft preparation: HRH; writing—review and editing: HRH and NJ; funding acquisition: JYH and NJ; resources: XCW, YJ, NJ, and JYH; supervision: JYH and NJ. All authors have read and agreed to the published version of the manuscript.

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Availability of data and materials
No datasets were generated or analyzed during the current study.

Declarations

Ethics approval and consent to participate
The study was conducted by the declaration of Helsinki and approved by the ethics subcommittee of West China Hospital of Sichuan University (WCHSCU_2023_317).

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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