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Research article

Postural balance disorders in sarcopenia based on surface electromyography

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ABSTRACT

Background: Sarcopenia is an intrinsic factor that leads to balance disorders and falls in older adults. However, the characterization of sarcopenia-related postural balance deficits remains unclear.

Aims: This study aimed to explore the balance performance and postural control strategy in older adults with sarcopenia during static stance tasks using force platforms and surface electromyography.

Methods: Older adults with right-sided dominance were recruited, including 27 adults with sarcopenia and 27 healthy counterparts. Postural sway was measured with eyes open/closed on rigid/compliant surfaces. The time- and frequency-domain indexes of bilateral lower extremity muscle activity were simultaneously recorded.

Results: The postural sway and activity of multiple lower extremity muscles in the sarcopenia group were increased ($P < 0.05$). The amplitude contribution ratio of the right tibialis anterior muscle (larger in sarcopenia), co-contraction ratio of right ankle dorsiflexion (smaller in sarcopenia), and mean power frequency and median frequency of the left gluteus maximus muscle (smaller in sarcopenia) had main effects of grouping ($P < 0.001$, $\eta_p^2 = 0.06$–0.10). All of them had discrimination for sarcopenia (area under the curve = 0.639–0.657, $P < 0.001$) and were correlated with balance function measurement in sarcopenia ($|r_s| = 0.22$–0.44, $P < 0.05$).

Conclusion: The results of this study suggest that older adults with sarcopenia have decreased balance function and increased cost of electrophysiology. They were found to prefer the postural strategy of dominant ankle dorsiflexion and demonstrated overactivity of the dominant tibialis anterior muscles and fatigue vulnerability of the nondominant gluteus maximus. Improvements in these postural features may have balance benefits.

1. Introduction

Approximately 28%–35 % of older adults fall each year worldwide [1]. Falls are the second biggest cause of accidental deaths globally, following injuries from traffic accidents [2]. Sarcopenia is an intrinsic factor that causes falls in older adults [3]. Some studies have supported the identification of sarcopenia for reducing the incidence of falls [3,4]. Balance dysfunction, which is caused by

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sarcopenia-related muscular weakening, has been reported to be the most consistent risk factor for fall prediction among older adults [5]. However, studies have demonstrated that balance dysfunction in older adults is related to muscle weakness or muscle mass reduction in several areas of the lower extremities [6–10]. Furthermore, the characteristics of balance deficits associated with sarcopenia remain unknown.

Biomechanical detection technologies can provide precise and detailed information on the quantitative measurement of balance function. The force platform's pressure receptors and acceleration sensors, in particular, track and record changes to the center of pressure (CoP) in real-time to reflect postural control status. However, research on its use in evaluating dynamic and static balance in sarcopenia is lacking. In addition, surface electromyography (sEMG) is an effective electrophysiological method for detecting motor unit recruitment and muscle work in a noninvasive and synchronous manner. Regarding the exploration of the postural balancing mechanism, sEMG can reveal the muscle contribution ratio, joint control strategy, and muscle fatigue. Considering that sarcopenia generates structural and functional abnormalities in the muscles, sEMG can serve as a useful tool for capturing sarcopenia-related balance quality and defect characteristics.

Therefore, to explore the balance function of sarcopenia, this study combined the force platform and sEMG technology. We hypothesized that older adults with sarcopenia would exhibit increased postural sway and muscle activity during standing activities as well as take some kind of compensatory postural strategy.

2. Materials and methods

2.1. Participants

A group of patients with sarcopenia was identified from the geriatric department of the hospital, and healthy individuals of the same age were recruited from the community. The final analysis sample comprised 27 individuals per group. They met the following criteria: (1) $\geq$60 years of age; (2) independently performing basic activities of daily living without the need for walking aids; (3) absence of neurological, vestibular, and orthopedic diseases or injuries that interfere with balance function; (4) absence of cognitive or emotional disorders; (5) absence of visual impairment; (6) the right leg as the dominant leg; (7) absence of change in physical condition and activity on the day before the test; and (8) provided informed consent. The diagnosis of sarcopenia was based on the consensus updated by the Asian Working Group for Sarcopenia in 2019 [11], and it consisted of low muscle mass combined with decreased handgrip strength or slow gait velocity. To calculate the appendicular skeletal muscle mass index (ASMI), InBody270 (Biospace Co., Ltd., Seoul, Korea), a body composition analyzer based on the multifrequency bioelectrical impedance method, was used.

On the basis of the sample size obtained and the effect size of the main results, we performed post-hoc power analysis. The power to detect the medium effect size observed in the study was >0.87. This study was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of the Affiliated Hospital of Xuzhou Medical University (No. XYFY2021-KL269-01).

2.2. Experimental procedure

Initially, participants completed the basic information registration and clinical balance function examination. Subsequently, they underwent static stability assessment on the force platform of a balance equipment and received synchronous telemetry of sEMG. Trained therapists, who were blinded to the grouping, led each stage of the test.

To collect EMG signals, the wireless sEMG acquisition system Desktop DTS (Noraxon Inc., Scottsdale, AZ, USA) was used with a 16-bit resolution, 2000-Hz sample rate, >100-dB common mode rejection ratio, and <1-μV baseline noise (root mean square). The gluteus maximus (GM), rectus femoris (RF), long head of the biceps femoris (LBF), tibialis anterior (TA), and lateral gastrocnemius (LGN) muscles on both sides were assessed. The target skin was prepared by shaving, scrubbing, rubbing with alcohol, and air drying to lessen skin resistance. The wireless sEMG sensors were fixed on the adjacent tendon or bone protrusion. The sensors had dimensions of 3.4 × 2.4 × 1.4 cm, a weight of 14 g, and an output of 100 mW. The attached electrodes were disposable silver/silver chloride gel bipolar electrodes. The electrodes were affixed to the midline of the abdomen of the target muscle and positioned parallel to the direction of the muscle fibers, referring to the Surface EMG for Noninvasive Assessment of Muscles of the European Recommendations for Surface ElectroMyoGraphy [12]. The desktop receiver was connected to the personal computer via universal serial bus and measured 19.7 × 29.2 × 6.4 cm in size. To synchronize with the equilibrium instrument test, the beginning and end of the sEMG recording were manually marked.

The force platform of the balance instrument (ProKin Line252, TecnoBody, Dalmine, Italy) contained four force sensors to detect the CoP location and reflect postural sway. The angular resolution and sampling frequency were 0.2° and 20 Hz, respectively. The measurement reliability of the balancer was verified elsewhere [13]. The static standing posture was evaluated under four scenarios, including eyes opened with rigid surface (EOR), eyes closed with rigid surface (ECR), eyes opened with compliant surface (EOC), and eyes closed with compliant surface (ECC). For each postural task, participants were instructed to adopt a standard stance (aligned to the calibration line of the force board) with the head facing straight and the upper limbs hanging naturally to the sides. Each task lasted for 30 s, and the rest time between tasks was 60 s. A sponge pad with a 35-kg/m^3 density served as the compliant surface.

2.3. Outcome measures

2.3.1. Clinical balance function tests

Four clinically standard tests for balance function were adopted. The functional reach test (FRT) assesses the maximum distance (cm) of forward arm extension [14]. The timed up and go test (TUG) measures the amount of time needed to complete consecutive functional activities, including sit–stand transition, walking 3 m, and turning [15]. Both the FRT and TUG were performed twice, and the average values were taken. The Berg balance scale (BBS) comprehensively examines the static and dynamic balance function under various functional activities on a scale of 56 points [16]. The Tinetti test, also known as performance-oriented mobility assessment (POMA) is a task-oriented test for evaluating gait and balance on a scale of 28 points [17]. The recorded FRT, BBS, and POMA values were directly proportional to the performance of balance function, whereas the TUG value was inversely proportional to the performance of balance function.

2.3.2. sEMG

The sEMG data were collected and processed using the MyoResearch XP software, version 3.16 (Noraxon Inc., Scottsdale, AZ, USA). Before analyzing the time-domain indexes, the raw sEMG data were rectified, filtered, and smoothed. The integrated EMG (iEMG), the area enclosed by the electromyogram curve during the test period, was subsequently reported. To account for individual and body part variations, the amplitude contribution ratio (ACR = iEMG of a given channel × 100 %/iEMG of all channels) [18] was further calculated. In addition, the co-contraction ratio (CCR = iEMG of antagonistic muscle × 100 %/iEMG of agonistic muscle + antagonistic muscle) [19] of knee flexion and ankle dorsiflexion was determined. Lower values of CCR indicated greater coordination of a particular joint or a greater propensity for contraction of the agonistic muscle. The raw sEMG data were subjected to fast Fourier transformation for spectral analysis. The obtained frequency-domain indexes included mean power frequency (MPF) and median frequency (MF). Muscle fatigue was found to manifest as sEMG signals in the low-frequency band.

2.3.3. Force platform

The first derivative of the CoP displacement as a function of time is the sway velocity, which is expressed in millimeters per second (mm/s). It was further divided into anteroposterior (AP, i.e., sagittal plane) and mediolateral (ML, i.e., frontal plane) sway velocities in the two-dimensional plane motion map. The sway perimeter (mm) indicates the length of the path taken by the CoP during the test. The sway area (mm^2) is the area of the location of 95 % of the CoP's envelope during the test. The greater the sway parameters, the lower is the stability of the participant.

2.4. Statistical analysis

Main statistical analyses were performed using Statistical Package for the Social Sciences (version 25, SPSS Inc., Chicago, IL, USA). Shapiro–Wilk test revealed that the iEMG, ACR, and postural sway parameters failed to fulfill normality. Quantitative data with normal distribution were expressed as mean ± standard deviation, and independent samples *t*-test was applied to compare groups. Quantitative data that were not normally distributed were expressed as medians (P_{25}, P_{75}), and Wilcoxon rank-sum test was used for between-group comparison. To examine the group and task differences in all sEMG indexes, two-way analysis of variance (ANOVA) was performed, in which the ACR was log-transformed for normalization. The effect size was expressed as partial eta squared (η_p^2). The category of the magnitude was small (0.01), medium (0.06), and large (0.14) [20]. Furthermore, to analyze the influence of sEMG indexes on sarcopenia, univariate logistic regression analysis was performed; the discrimination (i.e., the area under the curve [AUC]) of the corresponding predictive value was further calculated. Correlations between sEMG indexes and balance measures in each group were determined using Spearman's rank correlation test in R software, version 4.2.1 (R Foundation for Statistical Computing, Vienna, Austria). The correlation coefficient was expressed as r_s. We further drew correlation heatmaps using the corrplot package [21]. A two-sided *P* value of <0.05 was considered statistically significant.

Table 1
Between-group comparison of demographic and anthropometric data by gender ($\bar{x} \pm s$).

Variables	Male		*P* value	Female		*P* value
	Controls (n = 10)	Sarcopenia (n = 12)		Controls (n = 17)	Sarcopenia (n = 15)	
Age (years)	72.70 ± 4.19	76.58 ± 6.87	0.135	71.35 ± 4.33	72.93 ± 6.69	0.442
BMI (kg/m^2)	22.36 ± 2.66	21.10 ± 2.85	0.301	21.72 ± 2.56	20.72 ± 2.01	0.233
ASMI (kg/m^2)	7.41 ± 0.70	6.16 ± 0.41	<0.001	6.15 ± 0.58	5.31 ± 0.28	<0.001
Handgrip strength (kg)	34.12 ± 4.23	22.64 ± 3.85	<0.001	24.30 ± 6.55	16.80 ± 3.90	0.001
6-m gait speed (m/s)	1.09 ± 0.11	0.89 ± 0.10	<0.001	1.14 ± 0.12	0.87 ± 0.11	<0.001
TUG time (s)	10.81 ± 1.48	13.62 ± 2.91	0.012	9.75 ± 1.18	14.37 ± 2.84	<0.001
FRT distance (cm)	33.64 ± 3.59	22.06 ± 6.90	<0.001	30.61 ± 4.44	21.71 ± 5.18	<0.001
BBS score, 0–54	54.80 ± 1.55	46.08 ± 5.35	<0.001	54.29 ± 2.14	46.60 ± 5.62	<0.001
POMA score, 0–28	26.50 ± 1.08	22.08 ± 3.06	<0.001	26.94 ± 1.14	23.33 ± 2.85	<0.001

BMI, body mass index; ASMI, appendicular skeletal muscle index; TUG, timed up and go; FRT, functional reach test; BBS, Berg balance scale; POMA, performance-oriented mobility assessment.

3. Results

3.1. Basic characteristics

No significant difference in age and body mass index was noted between the sarcopenia and control groups (all $P > 0.05$). The sarcopenia group performed significantly worse in the clinical balance tests and sarcopenia diagnostic elements than the control group (all $P < 0.001$). These results are applicable to both the male and female subgroups (Table 1). No statistical difference in gender distribution was observed between the two groups ($\chi^2 = 0.307$, $P = 0.580$).

3.2. Postural sway

In the ECR task, no differences in any postural sway parameters were noted between the groups. The sarcopenia group had significantly larger AP sway velocity, ML sway velocity, and sway perimeter in the other three stance conditions than the control group, whereas the sway area was larger only in the ECC task (all $P < 0.05$) (Table 2).

3.3. Muscle activity

3.3.1. Intergroup difference

The between-group comparison of iEMG showed that the activity intensity of multiple lower extremity muscles in the sarcopenia group was higher throughout various stance activities ($P < 0.05$) (Fig. 1(a–d)). In each postural task, the sarcopenia group had higher total iEMG of the lower extremity muscles than the control group ($P < 0.05$) (Fig. 1(e)).

3.3.2. Main and interaction effects

The grouping task effects in the two-way ANOVA are presented in Table 3. The ACRs of the bilateral GM, right RF, right TA, and right LGN showed the moderate main effects of grouping ($P < 0.001$, $\eta_p^2 = 0.07$–0.09). The main effects of task were significant in the ACRs of the left GM and right TA with moderate effect sizes ($P < 0.01$, $\eta_p^2 = 0.07$–0.08). The CCRs of right ankle dorsiflexion showed the moderate main effects of grouping ($P < 0.01$, $\eta_p^2 = 0.10$), which were observed for the MPF and MF of the left GM ($P < 0.001$, $\eta_p^2 = 0.06$–0.07). The main effect of task was significant in the MPF of the right LGN with a moderate effect size ($P < 0.001$, $\eta_p^2 = 0.08$). All grouping × task interaction effects were not significant ($P > 0.05$), suggesting that the effects of sarcopenia on lower extremity muscle activity are independent of sensory information, including visual and plantar sensations.

As no interaction between grouping and task was observed, the main effect results and pairwise comparisons of grouping for the indicators reaching the medium effect size were directly analyzed. As shown in Table 4, except for the right TA, the ACRs of other muscles were smaller in the sarcopenia group than in the control group ($P < 0.001$). This finding suggested that sustaining multi-situational stance balance in sarcopenia involved relative overactivity of the TA on the dominant side. ACR is a log-converted variable; therefore, the difference in this index has no practical significance. The CCR of ankle dorsiflexion in the sarcopenia group was <50 % and 13.02 % ± 2.68 % lower than that in the control group (95 % confidence interval [CI] = 7.739–18.293, $P < 0.001$), indicating that the ankle dorsiflexion posture on the dominant side was adopted by the population with sarcopenia to maintain balance while standing. The combined MPF and MF data revealed that the contraction frequency of the GM on the nondominant side was lower in the sarcopenia group than in the control group. Moreover, the MPF of the left GM in the sarcopenia group was 30.08 ± 7.54 Hz lower than that in the control group (95 % CI = 15.219–44.944, $P < 0.001$), and the MF was 31.25 ± 8.37 Hz lower than that in the control group

Table 2
Between-group comparison of postural sway parameters in standing balance tasks (median [interquartile range]).

Tasks	Postural sway parameters	Controls	Sarcopenia	*P* value
EOR	AP sway velocity (mm/s)	7 (5, 8)	8 (6, 10)	0.026
	ML sway velocity (mm/s)	5 (4, 5)	6 (4, 9)	0.006
	Sway perimeter (mm)	288 (227, 318)	338 (274, 456)	0.007
	Sway area (mm^2)	169 (100, 268)	168 (97, 354)	0.716
ECR	AP sway velocity (mm/s)	11 (8, 15)	12 (9, 16)	0.214
	ML sway velocity (mm/s)	7 (5, 9)	7 (5, 11)	0.213
	Sway perimeter (mm)	407 (302, 565)	469 (374, 675)	0.180
	Sway area (mm^2)	263 (166, 548)	357 (278, 575)	0.261
EOC	AP sway velocity (mm/s)	9 (8, 11)	12 (8, 13)	0.037
	ML sway velocity (mm/s)	8 (6, 9)	10 (8, 13)	0.018
	Sway perimeter (mm)	439 (334, 481)	508 (414, 641)	0.015
	Sway area (mm^2)	320 (215, 441)	396 (230, 509)	0.239
ECC	AP sway velocity (mm/s)	20 (15, 24)	24 (18, 33)	0.025
	ML sway velocity (mm/s)	12 (8, 18)	16 (10, 24)	0.028
	Sway perimeter (mm)	759 (553, 967)	895 (738, 1309)	0.018
	Sway area (mm^2)	919 (521, 1434)	1406 (846, 1875)	0.014

AP, anteroposterior; ML, mediolateral; EOR, eyes opened with rigid surface; ECR, eyes closed with rigid surface; EOC, eyes opened with compliant surface; ECC, eyes closed with compliant surface.

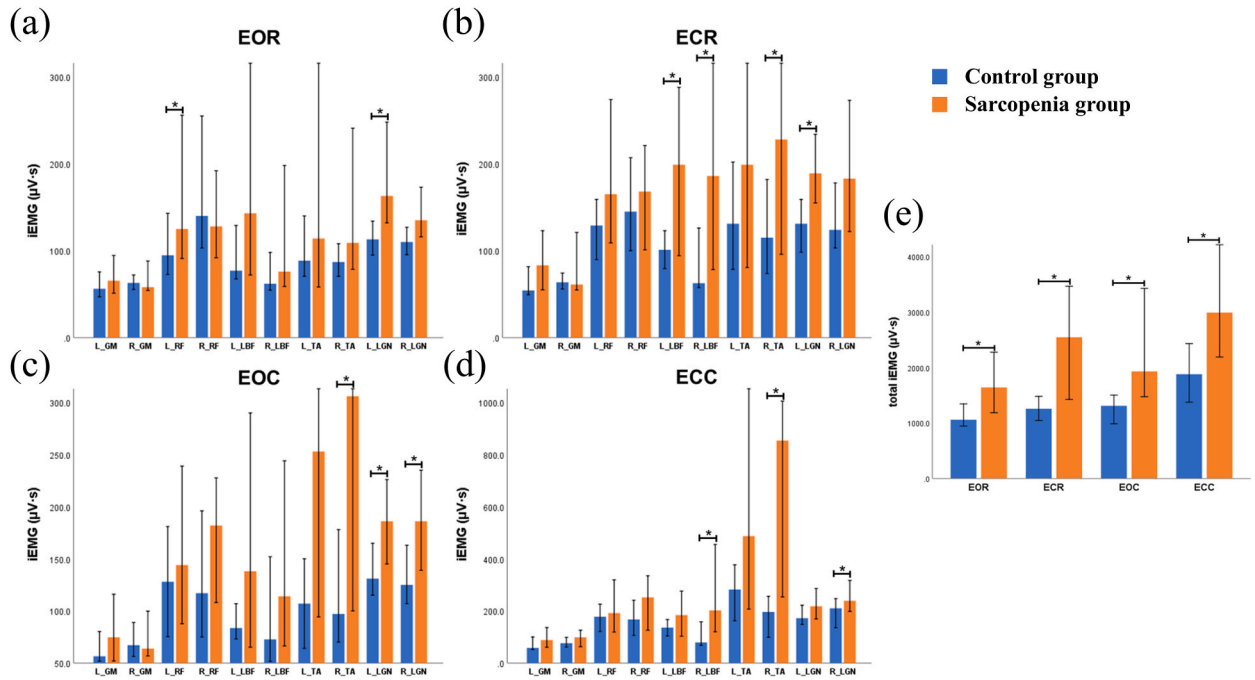

Fig. 1. Comparison of iEMG between groups.

(95 % CI = 14.758–47.748, $P < 0.001$).

3.3.3. *Regression and discrimination*

The sEMG indexes that were statistically significant in the regression for sarcopenia are shown in Table 5. The ACRs of the left GM, right RF, and right LGN as well as the CCRs of right knee flexion and ankle dorsiflexion were protective factors for sarcopenia (odds ratio [OR] < 1, $P < 0.01$), and they showed the negative classification direction for sarcopenia (AUC = 0.618–0.663, $P < 0.01$). Only the ACR of the right TA was a risk factor for sarcopenia (OR = 1.071, 95 % CI = 1.036–1.106, $P < 0.001$) and had a positive classification direction for sarcopenia (AUC = 0.644, $P < 0.001$). The MPF of the left GM and right LBF as well as the MF of the left GM were protective factors for sarcopenia (OR < 1, $P < 0.01$) and had a negative classification for sarcopenia (AUC = 0.604–0.657, $P < 0.01$). These findings suggested that the increased activation of the hip extensors, knee extensors, and ankle flexors of the dominant side; postural tendencies toward nonknee flexion and ankle dorsiflexion of the dominant side, and increased contraction frequency of the nondominant GM were associated with a lower risk of sarcopenia. Increased ankle extensor muscle activation was associated with a higher risk of sarcopenia.

3.4. *Correlation*

In the sarcopenia group, the ACRs of the LGN and the CCRs of ankle dorsiflexion on bilateral sides were negatively correlated with poor balance function ($|r_s| = 0.21$–0.47, $P < 0.05$), whereas the ACRs of the bilateral TA were positively correlated ($|r_s| = 0.24$–0.42, $P < 0.05$). Furthermore, the ACRs of the bilateral GM, although related to sway parameters, had little correlation with clinical balance function tests (Fig. 2(a)). The frequency-domain indexes of the bilateral GM and left RF were inversely associated with poor balance function ($|r_s| = 0.19$–0.56, $P < 0.05$) (Fig. 2(b and c)). These correlations were not observed in the control group (Fig. 3(a–c)).

4. Discussion

This study found that older adults with sarcopenia had increased postural sway and muscle activity. Both sarcopenia discrimination and balance-related criterion validity were present for the dominant ankle dorsiflexion postural strategy, dominant TA overactivity, and nondominant GM low contraction frequency.

Physiological parameters including the amount of muscle fiber recruitment, the level of motor unit synchronization, and the excitation conduction rate of muscle fibers can impact surface electromyographic signal detection. Strong individual variations exist among these parameters, which might have caused the absolute activation intensity to have a high standard deviation, as shown in Table 1. The between-group comparison of postural sway parameters showed that the ECR task showed no significance in any postural sway parameters between groups, whereas the EOR task showed significance. We speculate that blocking the visual input produced greater perturbations in the balance function of both groups; therefore, the difference between the groups was not significant during

Table 3
Grouping task effects for sEMG indexes of the lower extremity muscles ($\bar{x} \pm s$).

Variable	Muscles	Main effect of grouping		Main effect of task		Interaction effect	
		P value	η_p^2	*P* value	η_p^2	*P* value	η_p^2
lgACR	L_GM	<0.001	0.07	0.002	0.07	0.913	0.0
	R_GM	<0.001	0.09	0.021	0.05	0.711	0.01
	L_RF	0.026	0.02	0.686	0.01	0.370	0.02
	R_RF	<0.001	0.08	0.044	0.04	0.573	0.01
	L_LBF	0.336	0.0	0.043	0.04	0.496	0.01
	R_LBF	0.514	0.0	0.854	0.0	0.644	0.01
	L_TA	0.777	0.0	0.023	0.04	0.886	0.0
	R_TA	<0.001	0.07	0.001	0.08	0.272	0.02
	L_LGN	0.029	0.02	0.198	0.02	0.350	0.02
	R_LGN	<0.001	0.08	0.974	0.0	0.918	0.0
CCR	L_KJF	0.379	0.0	0.677	0.01	0.978	0.0
	R_KJF	0.002	0.05	0.594	0.01	0.537	0.01
	L_AJD	0.214	0.01	0.019	0.05	0.774	0.01
	R_AJD	<0.001	0.10	0.028	0.04	0.642	0.01
MPF	L_GM	<0.001	0.07	0.628	0.01	0.990	0.0
	R_GM	0.882	0.0	0.060	0.04	0.957	0.0
	L_RF	0.656	0.0	0.348	0.02	0.986	0.0
	R_RF	0.387	0.0	0.743	0.01	0.750	0.01
	L_LBF	0.516	0.0	0.303	0.02	0.744	0.01
	R_LBF	0.006	0.04	0.739	0.01	0.937	0.0
	L_TA	0.333	0.01	0.023	0.05	0.921	0.0
	R_TA	0.256	0.01	0.203	0.02	0.953	0.0
	L_LGN	0.036	0.02	0.262	0.02	0.594	0.01
	R_LGN	0.973	0.0	<0.001	0.08	0.586	0.01
MF	L_GM	<0.001	0.06	0.718	0.01	0.991	0.0
	R_GM	0.784	0.0	0.107	0.03	0.929	0.0
	L_RF	0.322	0.0	0.520	0.01	0.998	0.0
	R_RF	0.085	0.01	0.585	0.01	0.979	0.0
	L_LBF	0.648	0.0	0.587	0.01	0.840	0.0
	R_LBF	0.059	0.02	0.852	0.0	0.952	0.0
	L_TA	0.890	0.0	0.097	0.03	0.967	0.0
	R_TA	0.659	0.0	0.982	0.0	0.988	0.0
	L_LGN	0.375	0.0	0.194	0.02	0.600	0.01
	R_LGN	0.175	0.01	0.012	0.05	0.470	0.01

η_p^2, partial eta squared; lgACR, the logarithmic conversion form of the amplitude contribution ratio; CCR, co-contraction ratio; MPF, median power frequency; MF, mean frequency; L_GM, left gluteus maximus; R_GM, right gluteus maximus; L_RF, left rectus femoris; R_RF, right rectus femoris; L_LBF, long head of the left biceps femoris; R_LBF, long head of the right biceps femoris; L_TA, right tibialis anterior muscle; R_TA, right tibialis anterior muscle; L_LGN, lateral head of the left gastrocnemius muscle; R_LGN, lateral head of the right gastrocnemius muscle; L_KJF, left knee joint flexion; R_KJF, right knee joint flexion; L_AJD, left ankle joint dorsiflexion; R_AJD, right ankle joint dorsiflexion; sEMG, surface electromyography.

Table 4
Grouping main effect results and pairwise comparisons of sEMG indexes ($\bar{x} \pm SE$).

Variable	Muscles	Unweighted marginal mean		Pairwise comparisons	
		Controls	Sarcopenia	Difference	95 % CI
lgACR	L_GM	0.68 ± 0.02	0.56 ± 0.02	0.13 ± 0.03	(0.064, 0.187)*
	R_GM	0.73 ± 0.02	0.57 ± 0.02	0.16 ± 0.03	(0.091, 0.226)*
	R_RF	1.02 ± 0.03	0.85 ± 0.03	0.16 ± 0.04	(0.089, 0.238)*
	R_TA	0.97 ± 0.03	1.12 ± 0.03	−0.15 ± 0.04	(−0.225, −0.077)*
	R_LGN	1.04 ± 0.02	0.91 ± 0.02	0.13 ± 0.03	(0.071, 0.196)*
CCR	R_AJD	53.96 ± 1.89	40.94 ± 1.89	13.02 ± 2.68	(7.739, 18.293)*
MPF	L_GM	140.08 ± 5.33	109.99 ± 5.33	30.08 ± 7.54	(15.219, 44.944)*
MF	L_GM	105.49 ± 5.92	74.24 ± 5.92	31.25 ± 8.37	(14.758, 47.748)*

sEMG, surface electromyography; SE, standard error; CCR, co-contraction ratio; MPF, median power frequency; MF, mean frequency; CI, confidence interval; GM, gluteus maximus; RF, rectus femoris; TA, tibialis anterior; LGN, lateral head of the gastrocnemius; AJD, ankle joint dorsiflexion; lgACR, the logarithmic conversion form of the amplitude contribution ratio; *$P < 0.001$.

the ECR task. When the visual input is normal, the interference of sarcopenic illness is visible. In this study, the control group was unable to significantly increase the contribution of proprioception for maintaining balance compared with the sarcopenia group during visual blockade, suggesting that even in relatively healthy older adults, a certain degree of proprioceptive decline occurs. Both two-way ANOVA and regression analysis revealed that sarcopenia was positively correlated with the overactivity of the TA on the dominant side, postural tendencies of knee flexion and ankle dorsiflexion on the dominant side, and GM contraction frequency on the

Table 5
Univariate logistic regression and discrimination of sEMG indexes for sarcopenia.

Variable	Muscles	Regression			Discrimination		
		β	*P* value	OR (95 % CI)	Direction	AUC	*P* value
ACR	L_GM	−0.18	0.002	0.84 (0.748, 0.940)	–	0.642	<0.001
	R_RF	−0.08	<0.001	0.92 (0.884, 0.964)	–	0.663	<0.001
	R_TA	0.07	<0.001	1.07 (1.036, 1.106)	+	0.644	<0.001
	R_LGN	−0.07	0.005	0.93 (0.889, 0.979)	–	0.645	<0.001
CCR	R_ KJF	−0.02	0.002	0.98 (0.968, 0.993)	–	0.618	0.003
	R_AJD	−0.03	<0.001	0.97 (0.955, 0.982)	–	0.649	<0.001
MPF	L_GM	−0.01	<0.001	0.99 (0.985, 0.995)	–	0.657	<0.001
	R_LBF	−0.01	0.006	0.99 (0.984, 0.997)	–	0.604	0.008
	L_LGN	−0.01	0.039	0.99 (0.982, 0.999)	–	0.573	0.062
MF	L_GM	−0.01	<0.001	0.99 (0.987, 0.996)	–	0.639	<0.001

ACR, amplitude contribution ratio; CCR, co-contraction ratio; MPF, median power frequency; MF, mean frequency; OR, odds ratio; CI, confidence interval; AUC, area under the curve; GM, gluteus maximus; RF, rectus femoris; TA, tibialis anterior; LGN, lateral head of the gastrocnemius; KJF, knee joint flexion; AJD, ankle joint dorsiflexion; LBF, long head of the biceps femoris. " + " means a larger test result, indicating a more positive test, and " - " is the opposite.

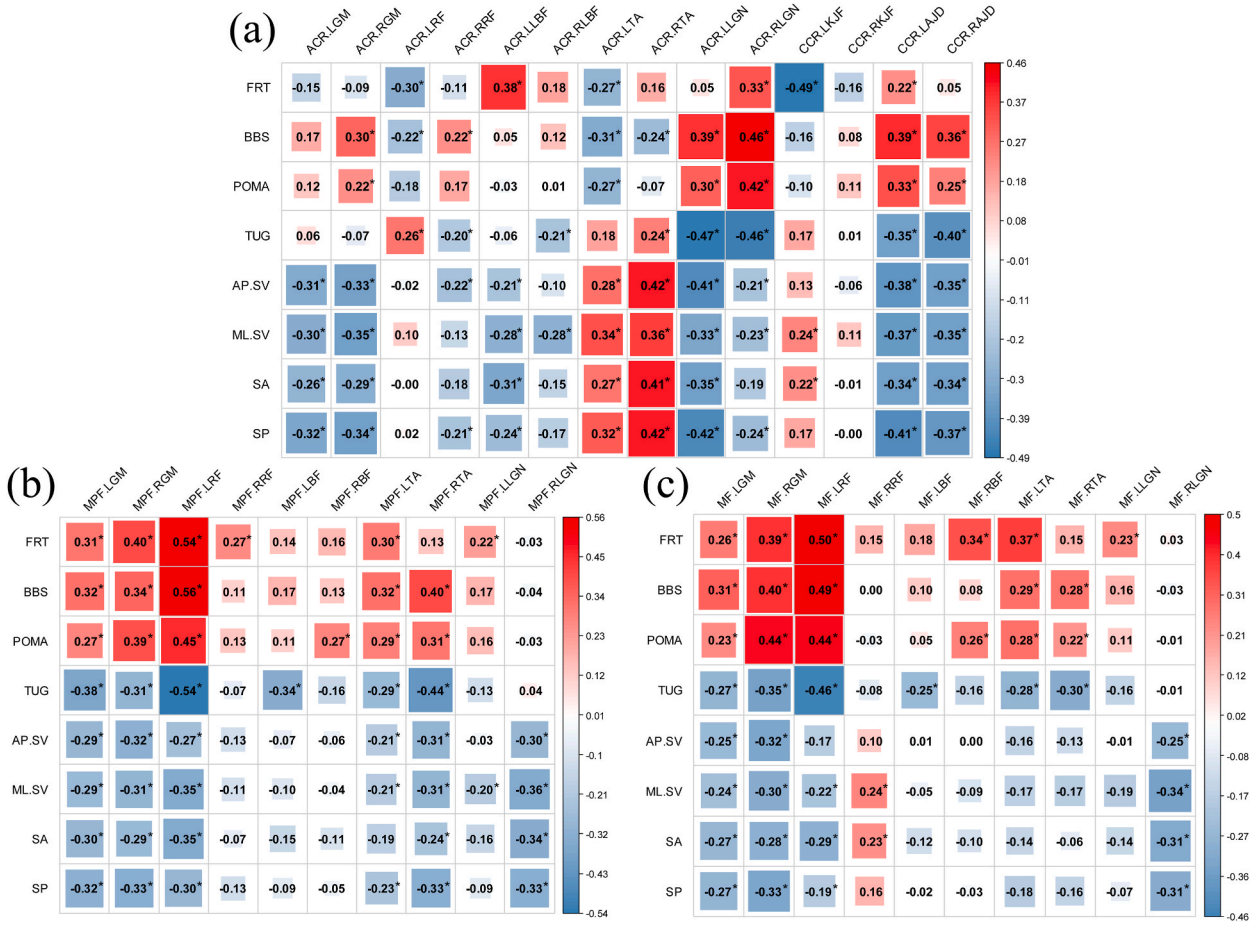

Fig. 2. Correlation heatmap of the sarcopenia group.

nondominant side. In addition, the negative correlation between sarcopenia and the dominant RF and nondominant GM suggested that increasing the proximal lower limb extensor activity aids in modifying the sarcopenic state. The correlation analysis revealed that the increased relative activity intensity of the TA, decreased relative activity intensity of the gastrocnemius, and ankle dorsiflexion strategy were related to poor balance function in sarcopenia. Therefore, excessive ankle dorsiflexion activities exacerbated participants' postural instability. Combining the two frequency indicators, it can be concluded that poor balancing function is correlated with the low muscle contraction frequency of the bilateral GM and nondominant side RF. We speculate that the bilateral GM plays a role in

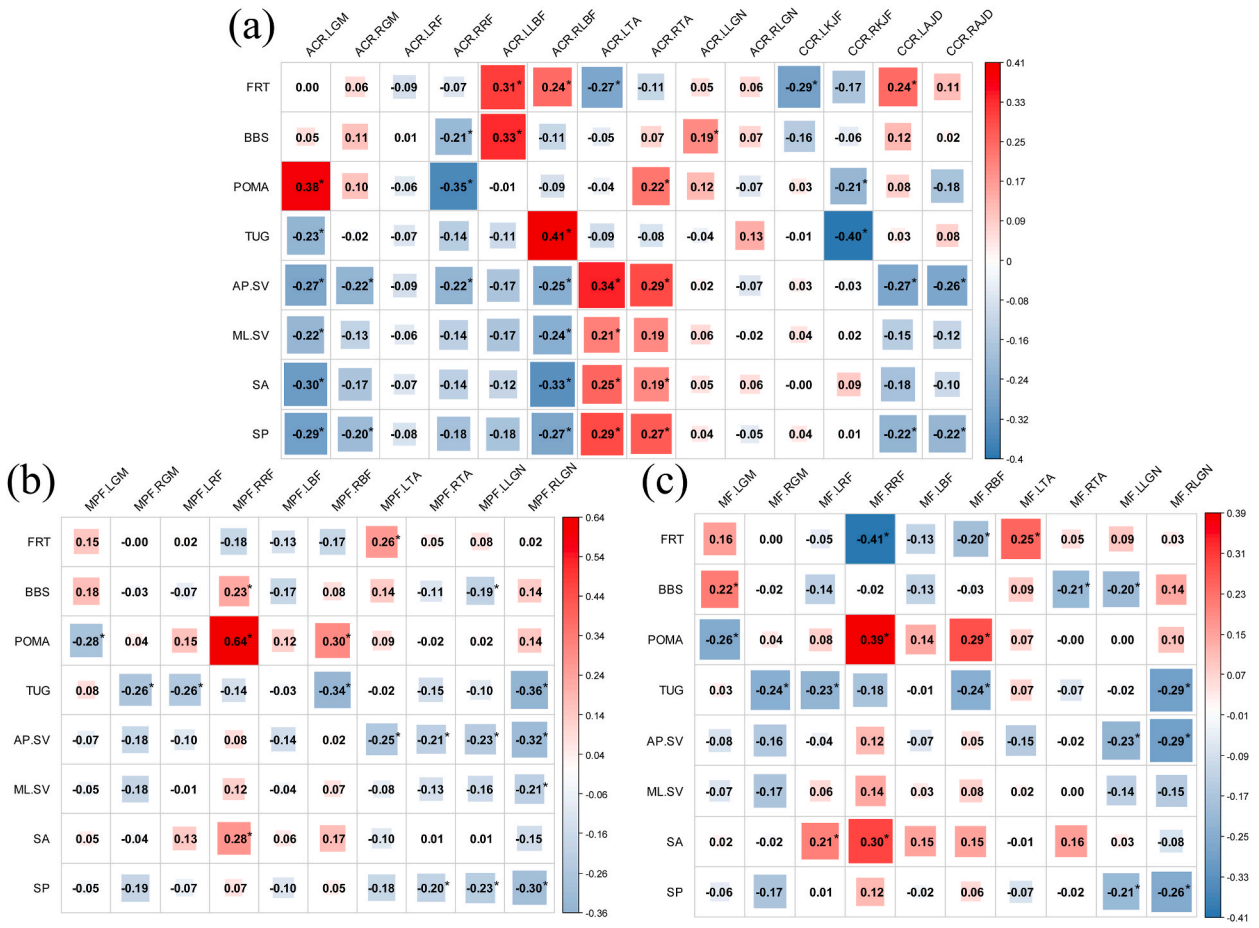

Fig. 3. Correlation heatmap of the control group.

trunk stabilization, whereas the RF on the nondominant side plays a supporting role and antagonistically contracts to stretch the knee joint to stabilize the lower limbs. A moderate association exists between the sEMG signal and balancing function, with the correlation coefficient falling between 0.3 and 0.5. Muscle activity signals were positively or negatively correlated with several balance metrics and eventually had a consistent correlation direction with the balancing function, suggesting that this connection is not coincidental. This association was only present in sarcopenia. Owing to the cross-sectional correlation, this study was unable to determine whether this pattern of muscle activity caused balance disorder or whether balance disorder induced this compensatory muscle activity.

The increased postural sway in sarcopenia based on the force platform detection supported the existence of sarcopenia-related balance impairment. Similar to the results of this study, older adults with RF or global sarcopenia had greater ML sway and fear of falling than those without sarcopenia during perturbed postural task [22] and were further associated with the severity of sarcopenia [23]. Targeted balance training with escalating difficulty is advised for individuals with sarcopenia in addition to appropriate treatment.

Despite a reduction in absolute muscle strength, sarcopenia increased the activity of muscles required for maintaining balance, particularly the absolute activation degree and relative contribution ratio of the TA. No significant difference in the size of compound muscle action potential was observed between sarcopenia and non-sarcopenia in the lower extremity muscles of older adults [24]. Therefore, in this study, sarcopenia with greater sEMG amplitude should have undergone stronger muscle contraction than the controls. Nevertheless, excessive postural sway remained inadequately controlled. These phenomena reflect the decreased neuromuscular postural control efficiency in sarcopenia in maintaining stance balance. The high activation ratio of the TA compared with other muscles may be related to its muscle fiber composition. The TA has more type 1 fibers, thereby structurally supporting its greater contribution to the postural role. In addition, the pathological alterations in sarcopenia mainly affect type 2 fibers (transition to type 1) [25], which may somewhat lower the sarcopenia risk in the TA. These speculations are supported by the lack of differences between groups with different sarcopenia stages in the motor unit potential area and motor unit number estimated of the TA [24,26]. Moreover, the adoption of the ankle dorsiflexion strategy may contribute to the high level of TA involvement. Although the difference in TA activity was only significant on the dominant side, the poor balance was related to bilateral TA overactivity. The functional training of other muscles in the lower extremities such as the GM or RF may have balance benefits.

The postural strategy of knee flexion and ankle dorsiflexion in sarcopenia indicates that individuals with sarcopenia tend to flex the

joints of their lower extremities with reduced joint angles and appear to gain stability by lowering their body's center of gravity. This postural strategy in the vertical direction is called the "suspensory strategy" and is often observed when exposed to strong external disturbances [27,28]. Compared with joint stiffness, the potential benefit of this compliant approach to joint flexion is the reduction in torque conflicts and internal frictions, which may alleviate rapid muscle fatigue around the knee and ankle joints. Consistent with TA overactivity, the ankle dorsiflexion strategy was linked to impaired balance in sarcopenia. Whether frequent ankle dorsiflexion movement is induced by sarcopenia-related balance defects or in turn exacerbates them remains to be elucidated.

MPF and MF are correlated with muscle fiber types and indicate the firing rate of muscle fibers during skeletal muscle contraction. A sign of muscle exhaustion is reduction in MPF and MF during muscle contraction. The low average contraction frequency indicates a vulnerability to tiredness. The low initial contraction frequency (i.e., a greater proportion of type 1 slow-twitch muscle fibers in the GM in sarcopenia) or the contraction frequency decreasing earlier and/or more (i.e., fatigue occurring earlier and/or being more severe in sarcopenia) may be related to the statistical difference in the average contraction frequency between the groups in this study. Our study demonstrated that sarcopenia not only reduces muscle strength but also affects muscle endurance in older adults, particularly of the GM on the nondominant side. Hip flexion, knee flexion, and ankle dorsiflexion frequently occur together in the kinematic chain of the lower limb, as they do in the suspensory strategy. In this situation, the GM must eccentrically contract to prevent excessive flexion and forward tumbling. The central fatigue caused by centrifugal contraction predominates [29] and is mainly characterized by a decrease in the ability of nerves to release impulses [30]. Owing to the restrictions of the bone structure, joint capsule, and ligaments, the knee joint is unlikely to adequately move in the sagittal plane. Therefore, for lateral coordination coupling, the ankle extension movement on the dominant side may require the hip extension movement on the nondominant side. Furthermore, in contrast to the dominant side, which performs functional activities, the nondominant side is frequently involved in stabilizing support [31], further contributing to the noticeable intergroup variations only in the nondominant side. The proximal muscle fatigue can increase the demand for distal muscle recruitment to counteract the interference effect on postural control [32]. In response to external perturbations including smaller muscle response amplitudes, slower onset latencies, and decreased muscle activation attenuation, muscle fatigue induces abnormalities in neuromuscular reflexes [33,34]. Moreover, antagonistic muscle engagement is altered as reflected in the increase in coactivity [35,36]. In this condition, the joints become more rigid and less flexible, thereby eventually deteriorating postural balance.

To the best of our knowledge, this is the first study to use sEMG and biomechanical detection technology to thoroughly investigate the pattern of sarcopenic balance dysfunction and provide a theoretical framework for the early diagnosis and correction of sarcopenia-related falls. In addition, this study focused on primary sarcopenia and the illness deficits of sarcopenia itself, explicitly omitting secondary sarcopenia and other disorders that clinically impair balance function. However, this study had some obvious limitations. First, we failed to rigorously analyze the timing and sequence of lower extremity muscle activation owing to the manual synchronization between force platform and sEMG measurements. Second, rather than reflecting the dynamic fatigue transition, the frequency-domain indexes used in this study represented the overall state during posture retention. Therefore, we avoided using "fatigue occurs" to describe between-group differences in frequency. Third, owing to the limited number of sensors in our laboratory, we primarily examined lower extremity muscles rather than trunk muscles. Fourth, to maintain homogeneity, which may restrict the generalizability of the findings, this study only included participants whose right side was dominant. Fifth, further subgroup analysis for examining the effects of sarcopenia severity and gender was constrained by the study's small sample size. Sixth, among the study participants with different genders and degrees of sarcopenia, the number of cases in some subgroups was small or the distribution between subgroups was uneven, and we failed to examine these differences. Finally, no three-dimensional photography was performed to assist in the investigation of performance and strategies of posture. The effects of nutritional intervention and exercise training on sarcopenia-related balance disorders should be further explored in a large sample population after upgrading the experimental methodologies.

5. Conclusions

The overactivity of the TA on the dominant side, the dorsiflexion strategy of the ankle, and the low contraction frequency of the GM on the nondominant side may be a cascade of postural responses to maintain standing balance in sarcopenia. These manifestations are features of sarcopenia-related balance defects and can guide clinical intervention.

Ethical statement

The Ethics Committee of the Affiliated Hospital of Xuzhou Medical University approved this research (No. XYFY2021-KL269-01).

Informed consent

All participants provided written informed consent before the study.

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Compliance with ethical standards

This manuscript describes original work that has not been published in part or entirety and is not under consideration for publication elsewhere. If accepted, the paper will not be published elsewhere in the same form, in English or any other language, including electronically, without the written consent of the copyright holder. All authors have read and confirmed that this manuscript adheres to the ethical standards of the journal.

Data availability statement

Data associated with the study has not been deposited into a publicly available repository. Data will be made available on request.

CRediT authorship contribution statement

Ting Zhang: Writing - review & editing, Writing - original draft, Visualization, Validation, Software, Project administration, Methodology, Formal analysis. **Yang Huo:** Resources, Investigation, Data curation. **Wenjing Yin:** Resources, Methodology, Investigation, Data curation. **Jie Xiang:** Writing - review & editing, Supervision, Project administration, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Jie Xiang reports financial support was provided by Ministry of Science and Technology of the People's Republic of China. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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