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Gait kinematic and kinetic characteristics among older adults with varying degrees of frailty: a cross-sectional study

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The aim of this study was to investigate the differences in gait kinematics and kinetics among pre-frail, frail, and non-frail older adults during routine walking tasks. A total of 106 older adult participants were classified into frail, pre-frail, and non-frail groups based on the Fried frailty scale. Kinematic and kinetic data were acquired via a three-dimensional gait analysis system. Multivariate analysis of covariance (MANCOVA) was employed to assess the differences in gait kinematics and kinetics among the groups, followed by Bonferroni post-hoc tests. MANCOVA revealed significant differences in peak ankle plantar flexion, ankle range of motion (ROM), knee heel strike angle, and hip toe-off angle among the groups on the right side ($P < 0.002$). On the left side, significant differences were found in peak ankle plantar flexion, ankle ROM, and hip toe-off angle ($P < 0.002$). However, no significant differences in gait kinetics were observed among the three groups ($P > 0.002$). There is a weak correlation between gait kinematic parameters and dynamic postural stability. Compared with non-frail individuals, frail older adults reduced peak ankle plantar flexion, ankle ROM, and knee heel strike angle during walking. In contrast, the hip toe-off angle was found to be increased in the frail group.

Keywords Older adults, Frailty, Gait, Kinematic, Kinetic

Abbreviations

MANCOVA	Multivariate analysis of covariance
ROM	Range of Motion
SSKG	Statokinesigram area
LOS	Limits of Stability
BMI	Body Mass Index
TUGT	Timed Up and Go Test
MMSE	Mini-Mental State Examination
SPPB	Short Physical Performance Battery
MNA-SF	Mini Nutritional Assessment-Short Form
GDS-15	Geriatric Depression Scale-Short Form
ANOVA	One-way Analysis of Variance
AIS	Athens Insomnia Scale

The global aging population is increasing at an unprecedented rate, with projections estimating that by 2050, over 2 billion individuals will be aged 65 years or older. A major concern among this aging population is frailty, a clinical syndrome with multiple causes and triggers characterized by a decline in strength, endurance, and physiological function, which significantly increases an individual's vulnerability to dependency, disability,

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and even death[1]. The prevalence of frailty among community-dwelling older adults is currently estimated at 18.8%[2]. To systematically quantify core health indicators in older adults, we implemented a multidimensional functional assessment framework, encompassing nutritional status, sleep quality, emotional state, cognitive function, and physical function[3,4]. These functional collectively constitute critical components of health status in the elderly population. Notably, age-related functional alterations may compromise gait stability and balance control through mechanisms such as diminished neuromuscular coordination[5]. The systematic implementation of these assessment tools enables precise identification of functional deficits in the elderly population, thereby establishing an evidence base for developing targeted intervention strategies.

Frail older adults are at an elevated risk for falls, which can lead to severe consequences such as disability, hospitalization, and even death[6]. Research has also shown that frailty reduces the quality of life of older adults and contributes to significant economic burdens and other negative outcomes[7–9]. Gait and balance dysfunction are key predictors of fall risk in older adults, underscoring the importance of assessing these factors in older adults, particularly those with known fall risk factors[10–12]. Early identification of frailty and timely intervention are critical to reducing adverse health outcomes, improving quality of life, and alleviating the broader social and economic burdens associated with aging[13].

Gait kinematics involves the analysis of joint angles and segment movements during walking. Previous studies have suggested that gait kinematic assessments can serve as valuable clinical tools for screening frailty in older adults[14–16]. Moreover, examining kinematic differences during specific phases of walking can provide further insights into changes in lower limb function and postural control strategies. However, there remains considerable uncertainty regarding the functional changes in lower limb joints across different levels of frailty in older adults. To address this gap, the present study employed a three-dimensional gait analysis system to conduct non-invasive, real-time, and continuous assessments of the hip, knee, and ankle. This approach allows the examination of gait characteristics and the ROM in various planes of the lower limb joints from a three-dimensional perspective. By analyzing gait kinematics and kinetics, this study aims to enhance our understanding of the physical functions of older adults. This will facilitate the early identification of frailty and pre-frailty, as well as the monitoring of the effectiveness of intervention strategies.

Although previous studies have extensively investigated the differences in gait kinematics between older and younger adults[17]. the biomechanical characteristics of older adults at different levels of frailty remain poorly understood. Early detection of gait disorders is crucial for effectively identifying pre-frail and frail older adults. Such identification can inform the development of targeted rehabilitation programs and provide appropriate guidance for improving their mobility and overall health. Therefore, the objective of this study was to examine the gait characteristics of older adults classified into three frailty states: frail, pre-frail, and non-frail.

Materials and methods

Participants

A total of 106 older adults were recruited from communities surrounding Fuzhou University Affiliated Provincial Hospital. which included 34 non-frail older adults, 52 pre-frail individuals, and 20 frail older adults. The frailty level of each participant was assessed via the Fried Frailty Phenotype, which consists of five components: (1) Unintentional body mass loss: body mass loss greater than 3 kg in the past six months, not due to dieting or exercise; (2) Weak grip strength: Grip strength measured using a Jamar Smart hand dynamometer. For men, grip strength is considered weak if it is less than 26 kg, and for women, less than 18 kg. The measurement is taken with the participant standing upright, feet naturally apart and arms at the sides, while grasping the dynamometer firmly with one hand. The value displayed on the device represents the grip strength; (3) Fatigue: Self-reported feelings of exhaustion or lack of energy for more than three days in the past week; (4) Slow walking speed: The time to walk 4.57 m is measured three times, with the minimum value used to calculate the walking speed. The threshold for slow walking speed is ≤ 0.76 m/s for men taller than 173 cm or women taller than 159 cm and ≤ 0.65 m/s for men ≤ 173 cm or women ≤ 159 cm; (5) Low physical activity: Weekly physical activity less than 600 MET-minutes, as measured by the short version of the International Physical Activity Questionnaire[18]. Individuals meeting three or more criteria were classified as frail, those fulfilling one or two criteria were categorized as prefrail, and those not meeting any of the five criteria were considered not frail. This study was approved by the ethics committee of our institution and complied with the World Medical Association Declaration of Helsinki. The study was performed from August 2023 to February 2024, All participants involved in our study provided written informed consent prior to their participation. The study protocol was approved by the Ethics Committee of Ethics Committee of Fuzhou University Affiliated Provincial Hospital (NO. K2022-09-029) and registered in Chinese Clinical Trial Registry Network (ChiCTR2300073905).

Inclusion and exclusion criteria

Inclusion criteria are as follows:

(1) Age 65–80 years;
(2) Able to walk independently[19];
(3) The ability to communicate and complete questionnaires and evaluations;
(4) Willing to participate in the study and sign the informed consent form.

Exclusion criteria are as follows:

(1) Hearing, vision, or severe cognitive impairment preventing participation;
(2) Acute injury, severe cardiopulmonary disease, terminal-stage malignant disease, or severe illness[20];
(3) History of mental illness or communication impairments preventing participation;

(4) Neurological or vestibular system diseases or severe musculoskeletal disorders affecting gait[14].

General data assessment

All the data were collected in a standardized manner by a specially trained research team. The demographic data included age, sex, body mass, height, body mass index (BMI), educational level, number of comorbidities, and number of medications.

Upper limb grip strength test

Grip strength was measured via a Jamar Smart hand dynamometer (USA). The participants were instructed to grip the dynamometer with maximum force, avoiding visual feedback and verbal encouragement. Three tests were performed with the dominant hand, and the average of the three values was recorded[21].

Timed up and go test (TUGT)

The TUGT reflects reaction time, agility, and dynamic balance ability[22].

Mini-cog

The Mini-Cog is a brief cognitive screening tool designed to identify cognitive impairment. which comprises three-word recall and clock drawing tests. A score of 0 is considered severe cognitive impairment[23].

Short physical performance battery (SPPB)

The SPPB is an objective tool used to assess lower limb function in older adults, particularly to determine their mobility or physical performance. It includes three parts: balance ability, walking speed, and a sit-to-stand test[24].

Mini nutritional Assessment-Short form (MNA-SF)

The MNA-SF is a well-established screening tool for identifying malnutrition in older adults. It includes six items: food intake in the past three months, body mass loss, mobility, acute illness or psychological stress, psychological problems, and BMI[25].

Geriatric depression Scale-Short form (GDS-15)

The GDS-15 is an objective tool used to assess depression levels[26].

Athens insomnia scale (AIS)

The AIS is a scale commonly used to assess the severity of insomnia, which comprises a total of 8 questions, with the first 5 focusing on nighttime sleep and the remaining 3 evaluating daytime functioning[27].

Gait analysis

Equipment

All participants underwent gait analysis at the Gait Laboratory of Fuzhou University Affiliated Provincial Hospital. Gait analysis was conducted via a SMART-D 400 infrared motion capture system (BTS, Italy). The data collection setup included eight infrared cameras (operating at 50 Hz), two synchronized cameras (BTS eVixta, operating at 40 Hz), four force platforms (BTS P6000D, operating at 2000 Hz), an information converter, and a computer system. Three-dimensional gait data were collected by reconstructing the trajectories of reflective markers placed on the participants' bodies, via infrared high-speed cameras to capture the movement. This allowed for the comprehensive analysis of gait parameters.

Procedure

The testing procedure was conducted as follows: Before the test, the participants were instructed to remove any reflective objects, and the room was prepared by closing doors and windows and drawing curtains to control the temperature. The testing equipment was calibrated to ensure proper positioning and connection of all infrared cameras to the computer system. The participants were then asked to remove their shoes and socks and change them into appropriate clothing. The following measurements were recorded: height, body mass, leg length, pelvic height, pelvic width, knee width, and ankle width. According to the Davis heel protocol, reflective markers (Infrared reflector balls) were attached to specific anatomical landmarks on both sides of the participant's body. These landmarks included the acromion, the 7th cervical vertebra, bilateral anterior superior iliac spine, between the posterior superior iliac spine, greater trochanter, lateral femoral condyle, fibular head, lateral malleolus, heel, and on the fifth metatarsal head. Additionally, small rods with markers were secured at the midpoint between the greater trochanter and lateral femoral condyle, as well as the midpoint between the fibular head and lateral malleolus on both sides. To establish a static standing model, participants were instructed to stand naturally with their arms at their sides and feet shoulder-width apart. The participants then performed the walking task by walking at their preferred speed along an 8-meter-long carpet path, back and forth, five times. Three gait cycles meeting the criteria of optimal image quality and natural walking posture were selected for further analysis.

Observed parameters

Kinematic parameters: These include the peak flexion and extension angles of the hip and knee joints, as well as the peak dorsiflexion and plantar flexion angles of the ankle. The ROM of the hip, knee, and ankle joints in the sagittal plane is also assessed. The ROM was quantified by determining the difference between the maximal and minimal values of flexion and extension in the sagittal plane for each joint throughout the entire gait cycle. Furthermore, the joint angles of the ankle, knee, and hip are measured at both heel strike and toe-off.

Kinetic parameters: These include the peak flexion and extension moments of the hip and knee joints, as well as the peak dorsiflexion and plantar flexion moments of the ankle joint.

Balance collection

Equipment

The HUBER® 360 neuromuscular control training and assessment system was utilized, which comprises several key components: a control screen, handles, a platform, a cushion, a hinged seat, a tablet computer, safety railings, and stability testing wedge blocks.

Procedure

The participants were tested in a quiet, well-lit indoor environment and maintained a calm state without excessive fatigue or other abnormal physical conditions. The participants stood naturally, with their bodies upright, and remained as still as possible. Their heels and toes were positioned at the corresponding points on the force platform, following the commands of the tester to complete the following actions.

1. Standing Posture on the Platform: Participants stood with both hands resting naturally at their sides and performed the following tasks:

   (1) Eyes open: The feet were positioned together, with heels touching and toes pointed outward at a 30-degree angle. Participants looked straight ahead and maintained their posture for 50 s;
   (2) Eyes closed: the same posture is repeated but with eyes closed for 50 s;

2. Single Leg Stand: Participants stood on either their left or right foot for 30 s;
3. Dynamic balance: After the test platform's lock was removed, the participants were instructed to stand on the platform with their feet grounded, maintaining balance while completing activities in different directions over a specified period.

Observed parameters

Bipedal eyes-closed statokinesigram area (SSKG) and eyes-open SSKG, left foot SSKG and right foot SSKG, and Limits of stability (LOS).

Statistical analysis

The data were analyzed via IBM SPSS Statistics 26.0. For continuous data that followed a normal distribution, the results are presented as mean ± standard deviation ($\bar{x} \pm s$). For non-normally distributed data, the median and interquartile range (M [*P*25, *P*75]) were used. Categorical data are presented as frequency (percentage) (n [%]). For baseline continuous variables and balance indicators, one-way analysis of variance (ANOVA) was performed if the data were normally distributed. If the data were non-normally distributed, the Kruskal-Wallis test was applied for non-parametric analysis. Categorical data were analyzed via the Chi-square test. A *P*-value of < 0.05 was considered statistically significant. MANCOVA was used to detect differences in gait parameters across the different groups, adjusting for age, sex, and BMI as covariates. For 12 spatial and temporal parameters, a $P < 0.004$ (0.05/12) was considered statistically significant in the MANCOVA. Bonferroni-corrected post hoc analysis was used for multiple comparisons between the three groups, with a significance threshold of $P < 0.0014$ [0.05/ (12*3)] for two-tailed tests. For 21 kinematic and kinetic parameters, a $P < 0.002$ (0.05/21) was considered statistically significant in the MANCOVA. Bonferroni-corrected post hoc analysis was used for multiple comparisons between the three groups, with a significance threshold of $P < 0.0008$ [0.05/ (21*3)] for two-tailed tests. The results are reported as effect sizes and *P* values.

Results

General demographic data of different frailty groups

The recruitment process is illustrated in Fig. 1. A total of 128 older adults were initially recruited, of whom 106 participants met the inclusion criteria and successfully completed the gait assessment.

Table 1 presents the demographic characteristics of the participants. Among the 106 eligible participants, 34 were classified as non-frail (32.1%), 52 as pre-frail (49.1%), and 20 as frail (18.9%) on the basis of Fried Frailty Phenotype. Comparative analysis revealed that the frail and pre-frail groups had significantly greater mean ages, TUGT scores, numbers of comorbidities, numbers of medications, and depression status than did the non-frail group ($P < 0.05$). However, no significant differences were observed among the three groups with regard to sex, body mass, height, BMI, educational level, nutritional status, or sleep quality ($P > 0.05$).

Gait Spatial and Temporal characteristics of different frailty groups

The MANCOVA results (Tables 2 and 3) revealed significant differences in several gait parameters among the three groups. Significant differences were found in the following parameters: gait speed ($F = 5.834$, $P < 0.0001$), right stride length ($F = 9.810$, $P < 0.0001$), left double support phase ($F = 6.742$, $P < 0.0001$), left step length ($F = 7.782$, $P < 0.0001$), and left stride length ($F = 9.034$, $P < 0.0001$).

Bonferroni post hoc analysis was performed to explore the differences and effect sizes between the frail/normal, pre-frail/normal, and pre-frail/frail groups (Tables 2 and 3). Compared with the non-frail group, the frail group exhibited significant reductions in the following parameters: gait speed decreased by 0.210 degrees (95% CI: 0.085–0.335, $P < 0.0001$), right stride length decreased by 0.181 degrees (95% CI: 0.080–0.282, $P < 0.0001$), left stride length decreased by 0.180 degrees (95% CI: 0.076–0.281, $P < 0.0001$), left step length decreased by

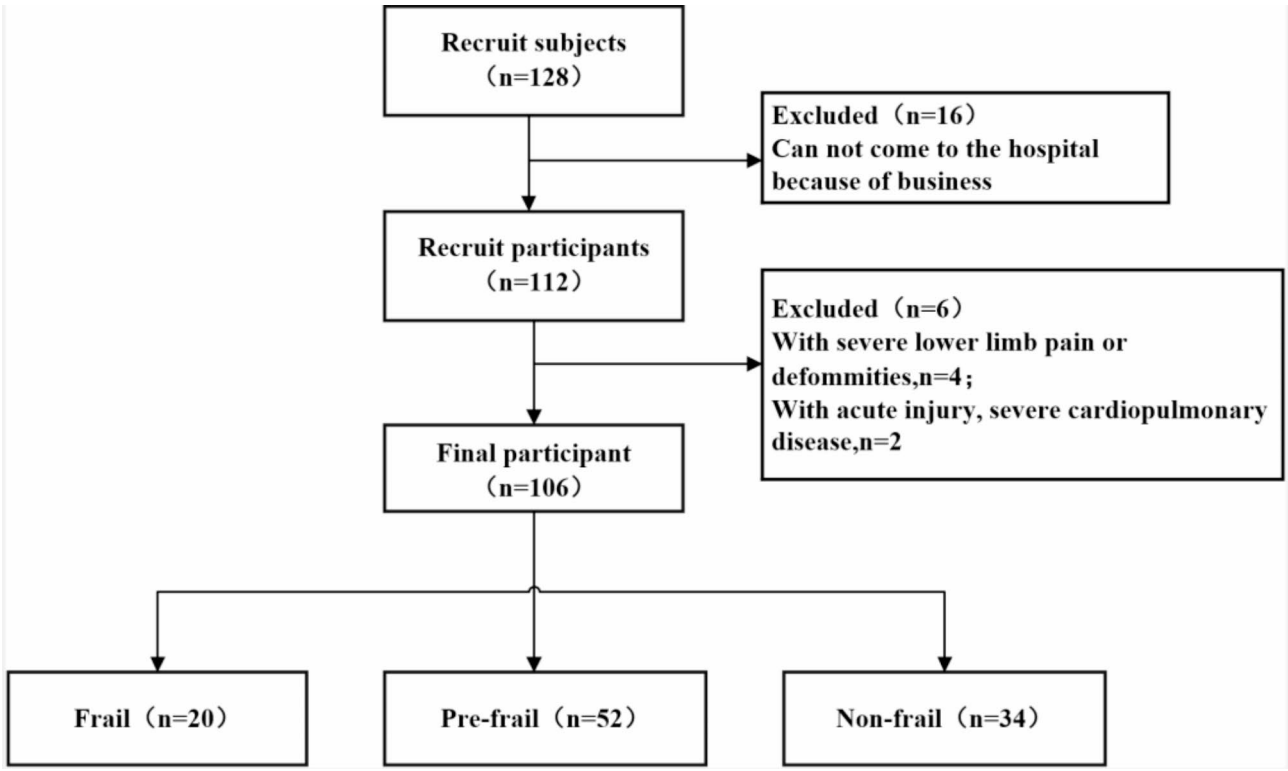

Fig. 1. Flowchart of the recruitment.

0.107 degrees (95% CI: 0.047–0.169, $P<0.0001$), and left double support phase increased by 4.715 degrees (95% CI: 2.500–6.930, $P<0.0001$).

Gait kinematic and kinetic characteristics of different frailty groups

The MANCOVA results (Tables 4 and 5; Fig. 2) revealed significant differences in several gait parameters among the three groups. For the right side, significant differences were found in the following parameters: ankle peak plantar flexion ($F=9.328$, $P<0.0001$), ankle ROM ($F=9.141$, $P<0.0001$), knee heel strike angle ($F=9.343$, $P<0.0001$), and hip toe-off angle ($F=8.630$, $P<0.0001$). For the left side, significant differences were observed in ankle peak plantar flexion ($F=6.380$, $P=0.002$), ankle ROM ($F=11.726$, $P<0.0001$), and hip toe-off angle ($F=7.246$, $P=0.001$). Furthermore, as frailty progressed, a decrease in knee ROM in the sagittal plane and an increase in the hip heel strike angle were noted.

Bonferroni post hoc analysis was performed to explore the differences and effect sizes between the frail/normal, pre-frail/normal, and pre-frail/frail groups (Tables 4 and 5). Compared with the non-frail group, the frail group exhibited significant reductions in the following parameters on the right side: Ankle peak plantar flexion decreased by 3.014 degrees (95% CI: 1.440–4.588, $P<0.0001$). Ankle ROM decreased by 3.747 degrees (95% CI: 1.779–5.716, $P<0.0001$). Knee heel strike angle decreased by 3.592 degrees (95% CI: 1.759–5.425, $P<0.0001$). Hip toe-off angle increased by 2.532 degrees (95% CI: 1.036–4.027, $P<0.0001$). Similarly, for the left side, the frail group showed significant changes compared with the non-frail group: Ankle peak plantar flexion decreased by 2.764 degrees (95% CI: 1.012–4.516, $P=0.001$). Ankle ROM decreased by 4.501 degrees (95% CI: 2.416–6.585, $P<0.0001$). Hip toe-off angle increased by 2.720 degrees (95% CI: 0.924–4.516, $P=0.001$). Kinetic Parameters: As shown in Tables 4 and 5, no significant differences in kinetic parameters were found among the three groups ($P>0.002$). Balance Parameters: There were statistically significant differences in bipedal eyes-closed SSKG ($F=9.748$, $P=0.008$), left foot SSKG ($F=11.657$, $P<0.001$), right foot SSKG ($F=11.080$, $P<0.001$) and LOS ($F=4.520$, $P=0.013$) among the three groups (Supplementary 1).

Correlation between Biomechanical parameters and clinical functional assessments

The correlation analysis revealed several significant relationships between biomechanical parameters and clinical functional assessments (Supplementary 2 and 3, Fig. 3). Specifically, the area of the bipedal eyes-closed SSKG was positively correlated with the right ankle peak plantar flexion ($r=0.198$) and negatively correlated with the right ankle ROM (r = -0.216). The right foot SSKG was negatively correlated with the right knee peak flexion angle (r = -0.280) and knee heel strike angle (r = -0.216), but positively correlated with the right hip toe-off angle ($r=0.208$). For the left foot SSKG, positive correlations were found with both the hip peak flexion angle ($r=0.241$) and the hip heel strike angle ($r=0.231$). The LOS were positively correlated with several joint angles, including the left ankle peak dorsiflexion ($r=0.255$), left ankle ROM ($r=0.225$), right knee peak flexion angle ($r=0.220$), right knee ROM ($r=0.230$), right knee toe-off angle ($r=0.240$), right hip peak flexion angle

Characteristics	Total ($n=106$)	Frail ($n=20$)	Prefrail ($n=52$)	No-faril ($n=34$)	F	P
Sex, n (%)					1.590*	0.451
Male	45 (42.5)	9 (45.0)	19 (36.5)	17 (50.0)		
Female	61 (57.5)	11 (55.0)	33 (63.5)	17 (50.0)		
Age (years)	71.40 ± 5.86	74.40 ± 6.06	71.12 ± 6.10	70.06 ± 4.82	3.759†	**0.027**
Height (cm)	159.79 ± 7.32	159.93 ± 8.54	159.36 ± 6.74	160.38 ± 7.58	0.203†	0.816
Body mass (kg)	62.20 ± 8.48	62.73 ± 10.11	62.68 ± 8.78	61.16 ± 7.05	0.374†	0.689
BMI (kg/m^2)	24.36 ± 3.15	24.55 ± 3.60	24.71 ± 3.26	23.73 ± 2.66	1.038†	0.358
Education level, n (%)					1.927‡	0.382
Elementary school	19 (17.9)	2 (10.0)	7 (13.5)	10 (29.4)		
Junior high school	23 (21.7)	3 (15.0)	16 (30.8)	4 (11.8)		
Senior high school	39 (36.8)	9 (45.0)	19 (36.5)	11 (32.4)		
University/College	25 (23.6)	6 (30.0)	10 (19.2)	9 (26.5)		
Grip strength (kg)	25.30 (20.28,29.23)	20.10 (17.13,24.65)	25.40 (20.85,29.20)	26.60 (21.68,32.00)	12.370‡	**0.002**
TUGT (s)	11.74 ± 3.03	15.15 ± 2.97	11.37 ± 2.68	10.31 ± 1.93	24.224‡	**< 0.001**
Comorbidity (n)	3.00 (2.00,4.00)	4.00 (3.00,5.00)	3.00 (1.00,4.00)	2.00 (1.00,3.25)	10.299‡	**0.006**
Medication (n)	2.00 (0.00,4.00)	4.00 (2.25,5.00)	2.00 (0.00,4.00)	1.00 (0.00,2.00)	16.221‡	**< 0.001**
SPPB, n (%)					9.115‡	**0.010**
Poor	4 (3.8)	1 (15.0)	3 (1.9)	0 (0.0)		
Average	42 (39.6)	11 (55.0)	19 (36.5)	12 (35.3)		
Good	60 (56.6)	6 (30.0)	32 (61.5)	22 (64.7)		
Nutritional status, n (%)					1.893‡	0.388
Malnutrition	4 (3.8)	1 (5.0)	3 (5.8)	0 (0.0)		
Risk of malnutrition	50 (47.2)	12 (60.0)	21 (40.4)	17 (50.0)		
Normal	52 (49.1)	7 (35.0)	28 (53.8)	17 (50.0)		
Depression status, n (%)					12.324‡	**0.002**
Depressive disorder	2 (1.9)	1 (5.0)	1 (1.9)	0 (0.0)		
Depression tendency	14 (13.2)	7 (35.0)	5 (9.6)	2 (5.9)		
Normal	90 (84.9)	12 (60.0)	46 (88.5)	32 (94.1)		
Sleep quality, n (%)					4.853‡	0.088
Insomnia	39 (36.8)	11 (55.0)	19 (36.5)	9 (26.5)		
Signify insomnia	21 (19.8)	2 (10.0)	14 (26.9)	5 (14.7)		
Normal	46 (43.4)	7 (35.0)	19 (36.5)	20 (58.8)		

Table 1. Participant characteristics. *BMI* body mass index. *Chi-Square Test, Values in bold are statistically significant, i.e., *p*-values < 0.05. †One-way ANOVA, Values in bold are statistically significant, i.e., *p*-values < 0.05. ‡Kruska–Walls Test, Values in bold are statistically significant, i.e., *p*-values < 0.05.

($r=0.234$), and right hip ROM ($r=0.222$). The SPBB was positively correlated with the right knee peak flexion angle ($r=0.193$) and left ankle ROM ($r=0.236$), but negatively correlated with several other gait parameters, including left ankle peak plantar flexion (r = -0.299), left ankle heel strike angle (r = -0.194), right ankle heel strike angle (r = -0.291), and right hip toe-off angle (r = -0.236). Finally, the TUGT score were positively correlated with multiple gait parameters, including the right ankle peak plantar flexion ($r=0.218$), right ankle heel strike angle ($r=0.198$), right ankle toe-off angle ($r=0.247$), right hip toe-off angle ($r=0.245$), left ankle peak plantar flexion ($r=0.293$), left ankle toe-off angle ($r=0.260$), and left hip toe-off angle ($r=0.229$). Conversely, the TUGT score was negatively correlated with the left ankle peak dorsiflexion (r = -0.227), left ankle ROM (r = -0.407), right knee peak flexion angle (r = -0.233), right knee ROM (r = -0.191), and right knee toe-off angle (r = -0.265) ($P<0.05$).

Discussion

While previous studies have explored differences in gait characteristics between older adults and younger individuals[17,28], there is limited research specifically compared the gait patterns of older adults with varying levels of frailty. Based on this, Our findings indicate that frailty significantly alters gait characteristics: frail older adults exhibit reduced bilateral ankle peak plantar flexion, decreased ankle ROM, and a smaller knee heel strike angle during level walking, in contrast to non-frail individuals. Additionally, the hip toe-off angle was found to be increased in frail individuals. These results emphasize that targeted functional exercise could help mitigate the adverse effects associated with frailty and improve functional outcomes in this population.

This study demonstrated that the risk of frailty increases with age, a finding consistent with numerous previous studies[29–31]. The aging process is associated with a progressive decline in various physiological functions, leading to reduced resistance to harmful external stimuli. Chronic diseases, multimorbidity, and polypharmacy are

Gait parameters Mean (SD)	Frail ($n=20$)	Prefrail ($n=52$)	No-faril ($n=34$)	MANCOVA F (p-value)*	Absolute difference		
					Frail vs. No-faril d, (p-value)†	Prefrail vs. No-faril d, (p-value)	Prefrail vs. faril d, (p-value)†
Stride time (s)	1.16 ± 0.18	1.10 ± 0.10	1.10 ± 0.12	1.203 (0.313)	0.41 (0.194)	0.00 (1.000)	0.47 (0.232)
Stance time (s)	0.71 ± 0.15	0.69 ± 0.09	0.67 ± 0.08	0.359 (0.875)	0.36 (0.666)	0.23 (1.000)	0.18 (1.000)
Swing time (s)	0.41 ± 0.06	0.42 ± 0.04	0.42 ± 0.05	0.820 (0.538)	0.19 (1.000)	0.00 (1.000)	0.21 (1.000)
Stance phase (%)	61.03 ± 7.76	62.25 ± 5.69	61.48 ± 2.34	0.532 (0.751)	0.09 (1.000)	0.16 (1.000)	0.19 (1.000)
Swing phase (%)	35.72 ± 4.05	37.88 ± 2.89	38.74 ± 2.24	3.988 (0.002)	1.00 (0.001)	0.32 (0.571)	0.67 (0.020)
Single support phase (%)	37.74 ± 5.66	38.69 ± 3.66	39.43 ± 2.13	1.596 (0.168)	0.44 (0.338)	0.24 (1.000)	0.22 (1.000)
Double support phase (%)	13.32 ± 3.16	12.45 ± 3.19	11.38 ± 2.65	1.260 (0.031)	0.68 (0.076)	0.36 (0.335)	0.27 (0.840)
Gait speed (m/s)	0.84 ± 0.21	0.99 ± 0.16	1.05 ± 0.19	**5.834 (< 0.001)**	**1.06 (< 0.0001)**	0.35 (0.505)	0.86 (0.005)‡
Cadence (step/min)	105.76 ± 14.19	109.51 ± 8.89	110.48 ± 11.20	1.010 (0.416)	0.38 (0.371)	0.10 (1.000)	0.35 (0.568)
Stride length (m)	0.95 ± 0.20	1.08 ± 0.14	1.13 ± 0.13	**9.810 (< 0.001)**	**1.13 (< 0.0001)**	0.37 (0.310)	0.82 (0.004)‡
Step length (m)	0.48 ± 0.14	0.54 ± 0.07	0.56 ± 0.08	4.208 (0.003)	0.76 (0.002)	0.27 (0.786)	0.64 (0.019)
Step width (m)	0.10 ± 0.04	0.10 ± 0.37	0.09 ± 0.04	0.496 (0.778)	0.25 (0.667)	0.03 (0.347)	0.00 (1.000)

Table 2. Comparison of spatial and temporal parameters on the right side among the three groups (MANCOVA). *MANCOVA with adjustment for age, BMI, gender, Values in bold are statistically significant, i.e., p-values < 0.004 for MANCOVAs. †Bonferroni correction was used in post-hoc comparisons across the three groups. Values in bold are statistically significant, i.e., p-values < 0.0014 for post-hoc tests. ‡A trend of difference between groups (0.0014 < p-values < 0.01 for MANCOVA and post-hoc tests).

Gait parameters Mean (SD)	Frail ($n=20$)	Prefrail ($n=52$)	No-faril ($n=34$)	MANCOVA F (p-value)*	Absolute difference		
					Frail vs. No-faril d, (p-value)†	Prefrail vs. No-faril d, (p-value)	Prefrail vs. faril d, (p-value)†
Stride time (s)	1.16 ± 0.18	1.11 ± 0.10	1.10 ± 0.12	0.784 (0.564)	0.41 (0.328)	0.09 (1.000)	0.39 (0.381)
Stance time (s)	0.73 ± 0.16	0.68 ± 0.09	0.67 ± 0.09	1.173 (0.328)	1.14 (0.173)	0.11 (1.000)	0.44 (0.214)
Swing time (s)	0.43 ± 0.06	0.43 ± 0.05	0.43 ± 0.04	0.433 (0.824)	0.00 (1.000)	0.00 (1.000)	0.00 (1.000)
Stance phase (%)	62.31 ± 5.72	60.98 ± 4.43	60.80 ± 2.29	1.335 (0.256)	0.39 (0.609)	0.05 (1.000)	0.28 (0.686)
Swing phase (%)	37.74 ± 5.63	38.43 ± 3.60	39.17 ± 2.39	1.177 (0.326)	0.36 (0.541)	0.23 (1.000)	0.16 (1.000)
Single support phase (%)	35.90 ± 4.83	37.65 ± 2.93	38.51 ± 2.42	2.581 (0.031)	0.75 (0.015)	0.31 (0.688)	0.49 (0.124)
Double support phase (%)	15.60 ± 5.40	11.84 ± 2.82	10.88 ± 1.86	**6.742 (< 0.001)**	**1.32 (< 0.0001)**	0.39 (0.542)	**1.02 (< 0.0001)**
Gait speed (m/s)	0.84 ± 0.21	0.99 ± 0.16	1.05 ± 0.19	**5.834 (< 0.001)**	**1.06 (< 0.0001)**	0.35 (0.505)	0.86 (0.005)‡
Cadence (step/min)	105.76 ± 14.19	109.51 ± 8.89	110.48 ± 11.20	1.010 (0.416)	0.38 (0.371)	0.10 (1.000)	0.35 (0.568)
Stride length (m)	0.95 ± 0.20	1.08 ± 0.14	1.13 ± 0.13	**9.034 (< 0.001)**	**1.13 (< 0.0001)**	0.37 (0.401)	0.82 (0.004)‡
Step length (m)	0.45 ± 0.11	0.53 ± 0.08	0.56 ± 0.08	**7.782 (< 0.001)**	**1.19 (< 0.0001)**	0.38 (0.326)	0.90 (0.004)‡
Step width (m)	0.10 ± 0.04	0.10 ± 0.37	0.09 ± 0.04	0.496 (0.778)	0.25 (0.667)	0.03 (0.347)	0.00 (1.000)

Table 3. Comparison of spatial and temporal parameters on the left side among the three groups (MANCOVA). *MANCOVA with adjustment for age, BMI, gender, Values in bold are statistically significant, i.e., p-values < 0.004 for MANCOVAs. †Bonferroni correction was used in post-hoc comparisons across the three groups. Values in bold are statistically significant, i.e., p-values < 0.0014 for post-hoc tests. ‡A trend of difference between groups (0.0014 < p-values < 0.01 for MANCOVA and post-hoc tests).

prevalent in older populations. Research has consistently shown a strong correlation between multimorbidity, polypharmacy, and the development of frailty[32–34]. Our study also revealed that the number of comorbidities and medications used increased as frailty progressed. In addition, we found that frailty was associated with a decline in muscle strength and physical function. Specifically, as frailty advanced, grip strength and SPPB scores decreased, whereas the TUGT time increased. Grip strength, Which is often used as an indicator of upper limb muscle strength, also reflects overall muscle strength and physical function in older adults. Thus, it serves as a key marker of frailty and sarcopenia in this population[35–37]. Similarly, the SPPB and TUGT are widely used clinical tools that assess walking speed, balance, and mobility, offering a comprehensive evaluation of physical function in older adults[38,39]. Our findings suggest that with advancing frailty, older adults experience decreases in muscle strength, balance ability, and overall physical function, which aligns with the results of most clinical studies on frailty. Moreover, this study also found that community-dwelling pre-frail and frail older adults are at increased risk of developing depressive symptoms. A systematic review revealed that older adults with depressive symptoms are more likely to develop frailty, and conversely, frail individuals are also at greater risk of experiencing depression[40,41]. The causes of depression in older adults are multifactorial and include physical health decline, cognitive impairment, social isolation, functional limitations, and the side effects of medications. In summary, as frailty progresses, the older adults experience changes in their comorbidity burden, medication

Gait parameters (degree/*N*.m/kg), mean (SD)	Frail ($n=20$)	Prefrail ($n=52$)	No-faril ($n=34$)	MANCOVA F (p-value)*	Absolute difference		
					Frail vs. No-faril d, (p-value)†	Prefrail vs. No-faril d, (p-value)†	Prefrail vs. faril d, (p-value)†
Ankle peak dorsiflexion angle	13.29 ± 3.45	12.97 ± 2.77	14.02 ± 2.74	1.049 (0.354)	0.24 (1.000)	0.38 (0.640)	0.11 (0.763)
Ankle peak plantar flexion angle	9.59 ± 1.81	11.71 ± 2.37	12.61 ± 2.43	**9.328 (< 0.0001)**	**1.36 (< 0.0001)**	0.94 (0.008)‡	0.37 (0.604)
Ankle ROM	22.89 ± 3.02	24.69 ± 2.69	26.63 ± 3.04	**9.141 (< 0.0001)**	**1.23 (< 0.0001)**	0.68 (0.008)‡	0.64 (0.057)
Ankle heel strike angle	0.55 ± 3.29	− 0.37 ± 3.29	− 0.23 ± 3.42	0.619 (0.541)	0.23 (1.000)	0.04 (1.000)	0.27 (0.885)
Ankle toe-off angle	5.10 ± 2.16	5.39 ± 4.33	5.96 ± 3.55	0.128 (0.880)	0.14 (1.000)	0.14 (1.000)	0.03 (1.000)
Knee peak flexion angle	58.63 ± 4.10	60.57 ± 4.35	61.32 ± 4.02	1.523 (0.223)	0.66 (0.075)	0.17 (1.000)	0.45 (0.248)
Knee peak extension angle	3.26 ± 2.54	2.01 ± 3.60	2.22 ± 2.81	1.984 (0.143)	0.38 (0.751)	0.06 (1.000)	0.37 (0.413)
Knee ROM	55.37 ± 3.83	58.56 ± 4.33	59.10 ± 4.09	5.045 (0.008)	0.93 (0.006)‡	0.13 (1.000)	0.72 (0.013)
Knee heel strike angle	9.46 ± 2.51	11.03 ± 2.51	13.05 ± 2.99	**9.343 (< 0.0001)**	**1.27 (< 0.0001)**	0.74 (0.003)‡	0.62 (0.081)
Knee toe-off angle	31.59 ± 4.72	34.11 ± 4.26	35.77 ± 4.63	4.120 (0.019)	0.89 (0.004)	0.37 (0.284)	0.57 (0.103)
Hip peak flexion angle	42.51 ± 4.29	43.16 ± 4.51	42.96 ± 3.71	0.144 (0.866)	0.11 (1.000)	0.05 (1.000)	0.14 (1.000)
Hip peak extension angle	0.50 ± 3.42	0.55 ± 4.26	1.84 ± 4.41	2.081 (0.130)	0.32 (0.768)	0.29 (0.498)	0.01 (1.000)
Hip ROM	43.01 ± 4.88	43.72 ± 3.74	44.79 ± 4.37	1.323 (0.271)	0.39 (0.396)	0.27 (0.887)	0.17 (1.000)
Hip heel strike angle	41.66 ± 6.66	40.28 ± 5.17	38.73 ± 4.36	4.130 (0.019)	0.55 (0.151)	0.32 (0.550)	0.24 (0.962)
Hip toe-off angle	10.12 ± 1.76	8.77 ± 2.24	7.59 ± 2.30	**8.630 (< 0.0001)**	**1.19 (< 0.0001)**	0.52 (0.048)	0.63 (0.060)
Ankle peak dorsiflexion moment	0.18 ± 0.71	0.13 ± 0.60	0.22 ± 0.69	0.308 (0.736)	0.05 (1.000)	0.14 (1.000)	0.07 (1.000)
Ankle peak plantarflexion moment	1.15 ± 0.46	1.40 ± 0.59	1.46 ± 0.71	0.843 (0.434)	0.49 (0.234)	0.09 (1.000)	0.44 (0.350)
Knee peak flexion moment	0.40 ± 0.41	0.53 ± 0.45	0.43 ± 0.46	0.884 (0.416)	0.06 (1.000)	0.29 (0.846)	0.22 (0.780)
Knee peak extension moment	0.28 ± 0.44	0.26 ± 0.43	0.27 ± 0.42	0.076 (0.927)	0.02 (1.000)	0.05 (1.000)	0.04 (1.000)
Hip peak flexion moment	0.25 ± 0.18	0.37 ± 0.29	0.38 ± 0.41	0.420 (0.658)	0.38 (0.380)	0.30 (1.000)	0.45 (0.435)
Hip peak extension moment	0.68 ± 0.36	0.77 ± 0.39	0.73 ± 0.36	0.506 (0.604)	0.14 (1.000)	0.11 (1.000)	0.24 (1.000)

Table 4. Comparison of gait kinematic and kinetic parameters on the right side among the three groups (MANCOVA). *ROM* range of motion. *MANCOVA with adjustment for age, BMI, gender, Values in bold are statistically significant, i.e., p-values < 0.002 for MANCOVAs. †Bonferroni correction was used in post-hoc comparisons across the three groups. Values in bold are statistically significant, i.e., p-values < 0.0008 for post-hoc tests. ‡A trend of difference between groups (0.0008 < p-values < 0.01 for MANCOVA and post-hoc tests).

use, physical function, and emotional health. Clinically, it is crucial to address these modifiable risk factors by focusing on early detection and intervention during the pre-frail stage. Effective management of these factors may help reduce the risk of frailty progression and mitigate its associated complications.

Gait analysis is a valuable tool for evaluating and improving physical movement by observing and measuring an individual's actions and posture during walking[42]. The results of this study show that, Compared to the non-frail groups, the frail group exhibited a decrease in gait speed, shorter step length, shorter stride length, and a prolonged double support phase, which is consistent with the majority of previous research[43,44]. These changes in gait parameters suggest that frailty has already affected the walking patterns of community-dwelling elderly individuals. Gait speed is a key indicator of functional ability and is widely used as a marker of frailty in older adults, as it can predict health outcomes[45,46]. This study found that, as frailty progresses, gait speed progressively declines, which aligns with earlier studies[47]. The double support phase is the most stable phase of the walking cycle. In the presence of walking difficulties, an extended double support phase is often the first compensatory response to enhance walking stability[48]. In frail elderly individuals, single-leg support may be insufficient to bear excessive body weight. To maintain balance and prevent falls, these individuals often adjust their gait by increasing the duration of the double support phase and shortening the single support phase. A substantial body of research has shown that, as age and muscle strength decline, gait patterns in the elderly often become rigid and uncoordinated. Frail elderly individuals adjust their gait strategy by shortening step length, stride length, and increasing double support time to maintain dynamic balance, thereby achieving a safer and more stable gait[49].

With the aging population, changes in gait, particularly a reduced ROM in the ankle joint, have become more prominent, impacting ankle joint function[50]. In this study, we also observed significant differences in ankle ROM across older adults with varying levels of frailty. Aging alters the structure and function of the central nervous system. Such as, significant thinning of the gray matter, slowing of cortical oscillation[51,52], loss of neurons in the spinal cord, and lack of spinal reflex modulation[53]. Owing to these changes in the central nervous system pose greater challenges for the elderly in terms of sensory integration and motor execution for postural control[54]. Consequently, it results in diminished mobility when they are walking. Further analysis revealed that frail older adults exhibited a significantly smaller ankle plantar flexion angle than non-frail individuals did. This reduction in ankle flexion may be a compensatory mechanism: when the body perceives instability, it often responds by decreasing joint flexion angles[55,56]. These findings suggest that frail older adults may adopt a more cautious gait to maintain balance and reduce the risk of falls. Additionally, the decline in lower limb muscle function in frail older adults individuals, particularly the weakening of the ankle plantar flexor muscles, leads to a diminished

Gait parameters (degree/*N* m/kg), mean (SD)	Frail ($n=20$)	Prefrail ($n=52$)	No-faril ($n=34$)	MANCOVA F (p-value)*	Absolute difference†		
					Frail vs. No-faril d, (p-value)	Prefrail vs. No-faril d, (p-value)	Prefrail vs. faril d, (p-value)
Ankle peak dorsiflexion angle	12.29 ± 3.10	12.94 ± 2.28	14.03 ± 2.20	3.160 (0.047)	0.67 (0.038)	0.48 (0.136)	0.26 (0.929)
Ankle peak plantar flexion angle	9.77 ± 2.86	11.79 ± 2.42	12.53 ± 2.58	**6.380 (0.002)**	1.10 (0.001)‡	0.31 (0.581)	0.79 (0.010)
Ankle ROM	22.06 ± 3.69	24.73 ± 2.62	26.56 ± 3.22	**11.726 (< 0.0001)**	**1.32 (< 0.0001)**	0.63 (0.023)	0.91 (0.003)‡
Ankle heel strike angle	0.39 ± 3.27	− 0.64 ± 3.26	0.10 ± 3.40	1.008 (0.368)	0.09 (1.000)	0.23 (0.942)	0.32 (0.728)
Ankle toe-off angle	5.21 ± 2.41	5.83 ± 4.88	6.09 ± 4.10	0.052 (0.949)	0.24 (1.000)	0.06 (1.000)	0.14 (1.000)
Knee peak flexion angle	58.35 ± 4.06	60.30 ± 4.89	62.03 ± 3.85	2.427 (0.094)	0.94 (0.012)	0.38 (0.239)	0.42 (0.292)
Knee peak extension angle	3.31 ± 2.33	2.10 ± 3.93	2.26 ± 3.24	1.237 (0.295)	0.36 (0.860)	0.04 (1.000)	0.40 (0.560)
Knee ROM	55.04 ± 3.73	58.20 ± 5.10	59.76 ± 4.91	4.396 (0.015)	1.05 (0.002)‡	0.31 (0.432)	0.66 (0.042)
Knee heel strike angle	11.15 ± 2.76	11.51 ± 2.88	12.71 ± 3.08	1.525 (0.223)	0.53 (0.182)	0.41 (0.198)	0.13 (1.000)
Knee toe-off angle	32.57 ± 5.22	34.41 ± 7.44	35.52 ± 5.06	1.083 (0.343)	0.27 (0.308)	0.17 (1.000)	0.27 (0.822)
Hip peak flexion angle	44.00 ± 6.22	42.49 ± 5.98	42.60 ± 4.19	0.958 (0.387)	0.28 (1.000)	0.02 (1.000)	0.24 (0.906)
Hip peak extension angle	0.05 ± 3.56	0.09 ± 4.62	2.38 ± 4.21	4.458 (0.014)	0.58 (0.173)	0.48 (0.053)	0.01 (1.000)
Hip ROM	44.05 ± 6.34	42.59 ± 5.11	44.99 ± 5.53	1.794 (0.172)	0.16 (1.000)	0.45 (0.149)	0.27 (0.934)
Hip heel strike angle	42.00 ± 8.73	40.60 ± 5.55	39.23 ± 5.15	2.439 (0.092)	0.41 (0.341)	0.25 (0.946)	0.21 (1.000)
Hip toe-off angle	10.44 ± 2.27	8.66 ± 2.78	7.71 ± 2.56	**7.246 (0.001)**	1.11 (0.001)‡	0.35 (0.317)	0.67 (0.034)
Ankle peak dorsiflexion moment	0.11 ± 0.41	0.17 ± 0.52	0.22 ± 0.69	0.325 (0.724)	0.18 (1.000)	0.08 (1.000)	0.12 (1.000)
Ankle peak plantar flexion moment	1.27 ± 0.67	1.33 ± 0.55	1.53 ± 0.25	1.881 (0.158)	0.58 (0.196)	0.44 (0.247)	0.10 (1.000)
Knee peak flexion moment	0.33 ± 0.38	0.41 ± 0.24	0.34 ± 0.35	0.773 (0.464)	0.03 (1.000)	0.24 (0.992)	0.52 (1.000)
Knee peak extension moment	0.36 ± 0.31	0.29 ± 0.32	0.31 ± 0.24	0.189 (0.828)	0.18 (1.000)	0.07 (1.000)	0.22 (1.000)
Hip peak flexion moment	0.33 ± 0.43	0.40 ± 0.25	0.40 ± 0.33	0.173 (0.841)	0.18 (1.000)	0.00 (1.000)	0.22 (1.000)
Hip peak extension moment	0.52 ± 0.27	0.63 ± 0.30	0.72 ± 0.22	1.643 (0.199)	0.83 (0.033)	0.33 (0.422)	0.37 (0.390)

Table 5. Comparison of gait kinematic and kinetic parameters on the left side among the three groups (MANCOVA). *ROM* range of motion. *MANCOVA with adjustment for age, BMI, gender, Values in bold are statistically significant, i.e., p-values < 0.002 for MANCOVAs. †Bonferroni correction was used in post-hoc comparisons across the three groups. Values in bold are statistically significant, i.e., p-values < 0.0008 for post-hoc tests. ‡A trend of difference between groups (0.0008 < p-values < 0.01 for MANCOVA and post-hoc tests).

ankle plantar flexion angle[57,58]. This manifests as shorter step lengths, reduced foot clearance, and poorer ankle stability, ultimately resulting in abnormal gait patterns[59].

The heel strike marks the beginning of the gait cycle, during which the lower limb joints-particularly the hip, knee, and ankle-initiate movements to accommodate the demands of walking[60]. Conversely, toe-off marks the end of the gait cycle, where joint and muscle coordination in the lower limbs is crucial for maintaining balance, decelerating, absorbing shock, and preparing for the next step. In our study, we found that as frailty progressed, the knee heel strike flexion angle decreased. This may indicate the early stages of a shuffling gait, which can lead to a lack of stability during the walking support phase among older adults, thereby heightening the risk of falls[61]. Additionally, compared with non-frail individuals, the frail older adults presented an increased hip toe-off flexion angle. This may be attributed to the decline in physical function associated with frailty, particularly the weakness of the quadriceps femoris and gluteus medius muscles, which are insufficient to support the body during forward swing, thereby resulting in an increased hip toe-off flexion angle. Aging is associated with a decline in neuronal density, synaptic integrity, as well as neurotransmitter availability, which may disrupt normal brain function and subsequently alter muscle activation patterns[62,63]. These changes can contribute to the observed modifications in gait among older adults. Future research we will employ electromyography to quantitatively and qualitatively assess neuromuscular activity and activation, aiming to elucidate the peripheral biomechanical mechanisms underlying frailty and postural stability. Post hoc comparisons revealed significant differences in these gait parameters between frail and non-frail individuals, but no significant differences were found between the pre-frail and non-frail groups. These findings suggest that gait changes differ between pre-frail and frail older adults, with the frail group showing more pronounced alterations in gait at normal walking speeds. Although the differences did not reach statistical significance after adjustment, they may have clinical implications for guiding the rehabilitation of pre-frail older adults. Muscle activation patterns, joint loading, and neural control mechanisms that could contribute to the observed differences in gait kinematics among older adults with varying degrees of frailty. On the basis of these findings, we believe that comprehensive lower limb muscle strengthening and dynamic balance training are essential for both pre-frail and frail older adults[64]. Previous studies have also shown that early interventions, including posture correction, maintaining ankle flexibility, and strengthening lower limb muscles, can help delay the progression from non-frail and pre-frail states to full frailty[65].

Maintaining postural balance is a multifaceted process, and the assessment of postural stability has become a critical tool for understanding fall mechanisms and developing effective prevention strategies for the older

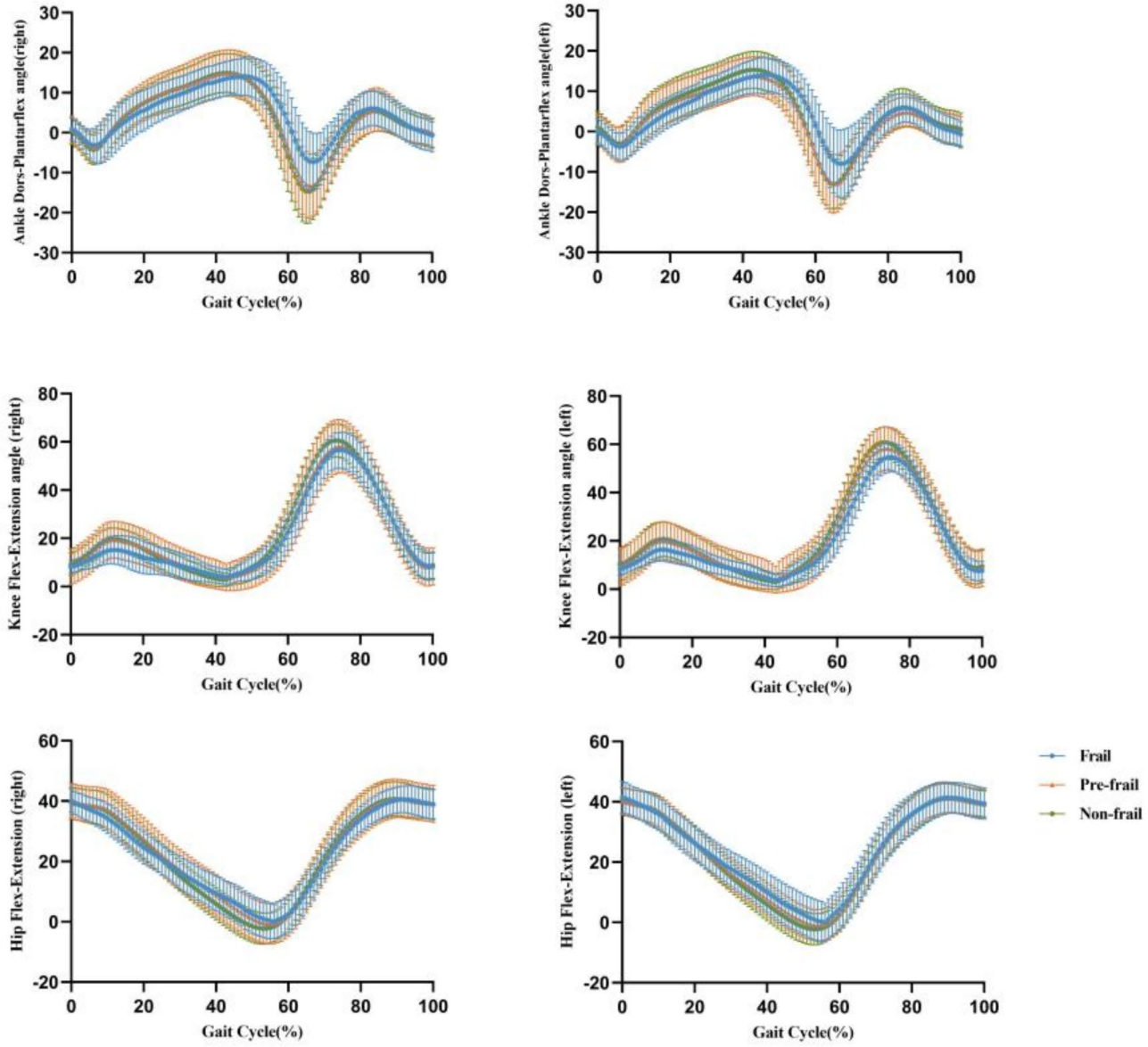

Fig. 2. Sagittal plane gait cycle diagrams of the hip, knee, and ankle joints.

adults[66,67]. The SSKG parameter reflects the area traversed by the body's center of pressure, which can serve as an indicator of balance disorders[68,69]. A larger SSKG area indicates a greater range of motion and poorer standing stability, suggesting more severe balance impairments. LOS is determined by the planar area of the octagon formed by connecting the maximal center of pressure excursion points achieved in each direction[70]. This metric quantifies an individual's capacity to shift their center of gravity within the bounds of postural stability and is widely utilized in evaluating postural control and balance[71]. Our findings revealed that frail and pre-frail individuals exhibited significantly larger bipedal eyes-closed SSKG and single-leg SSKG areas, as well as lower LOS, than non-frail individuals did. These results suggest that frail and pre-frail older adults experience greater postural sway and have impaired balance function, which is consistent with the decline in balance control associated with aging[72]. Consequently, these findings emphasize the importance of prioritizing balance function assessments in clinical settings to mitigate fall risk in older adults.

Additionally, we examined the correlation between biomechanical parameters and clinical functional assessments. The majority of gait parameters that differed between the group in our study were correlated with balance-related measures, including the SPPB and TUGT scores. These findings suggest that gait abnormalities in older individuals are linked to alterations in both physical function and balance ability. Previous research has shown that changes in gait, such as reduced walking speed, shorter step lengths, and increased stride length variability, are associated with a greater risk of falls and loss of balance[67]. However, this study found that there is a weak correlation between kinematic parameters and postural stability. This may be influenced by such factors as compensation mechanisms, physiological mechanism difference. Limited research has investigated the

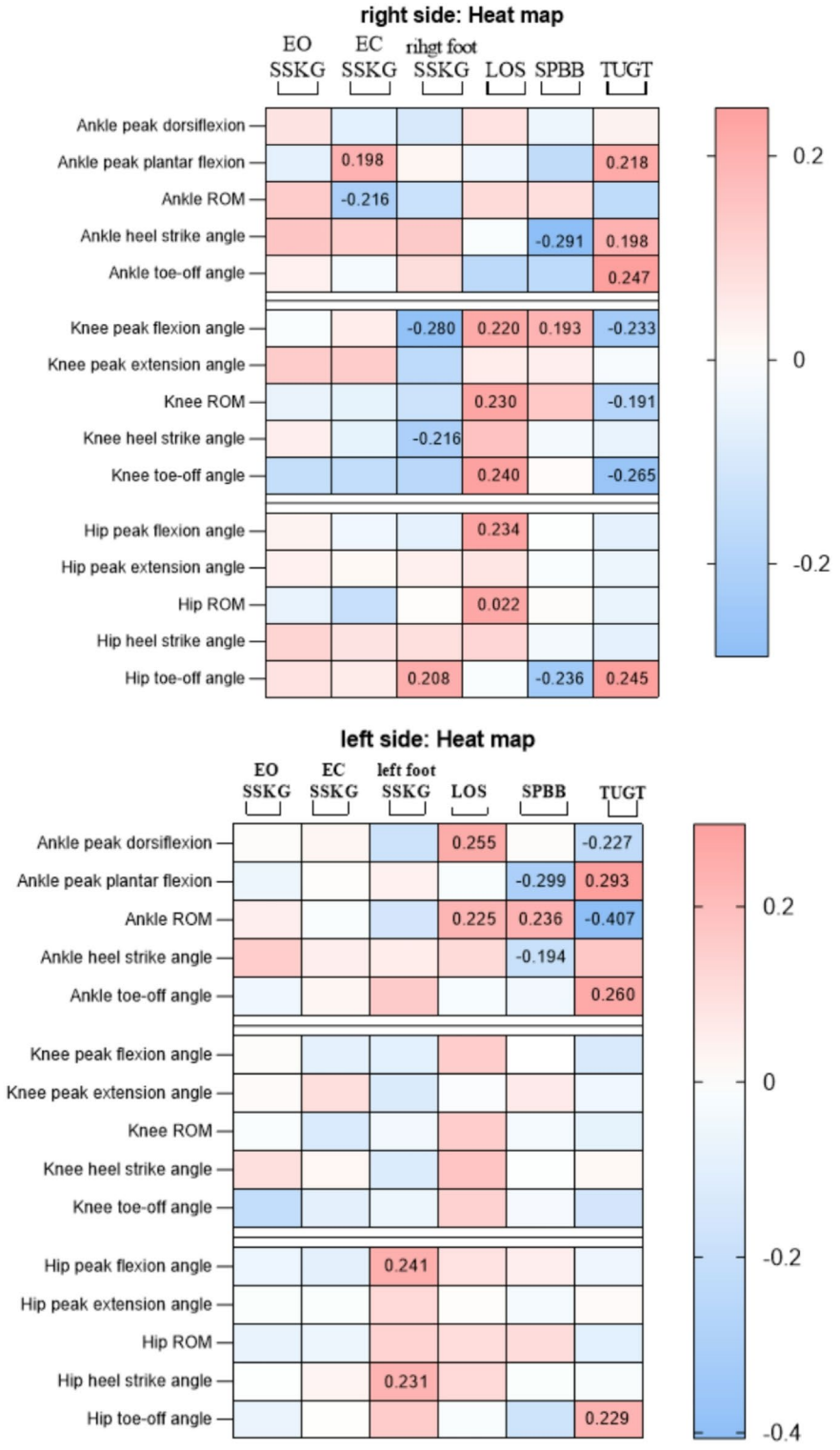

Fig. 3. Correlations between SPPB, TUGT, balance parameters and kinematic parameters. *SPPB* Short Physical Performance Battery, *TUGT* Timed Up and Go Test, *ROM* range of motion, *SSKG* Statokinesigram area, *LOS* Limits of Stability, *EO* Eyes-Open, *EC* Eyes-Closed.

correlation between kinematic parameters and balance function in elderly populations, thus additional studies are warranted to explore this relationship further.

On the basis of these findings, we propose that frailty status in older adults is closely associated with gait characteristics, and that gait changes may serve as subclinical indicators of frailty. Monitoring clinical gait parameters in the older adults can provide valuable insights for predicting frailty and other adverse health

outcomes, while also contributing to a better understanding of the biomechanical mechanisms that underpin diminished postural stability in frail older adults.

Limitations

Although this study provides valuable insights, several limitations must be acknowledged. First, the sample size, particularly in the frail group, was limited. The focus on community-dwelling older adults may have contributed to this limitation, as frail individuals often present with more complex mobility issues and comorbidities. To obtain a more representative sample, future studies should consider recruiting participants from hospital settings, which may better reflect the broader frail older adults. Second, there is a lack of research on the biomechanical indicators of lower limb function across different frailty statuses. The scarcity of reference data in this area hinders the development of a comprehensive understanding of frailty-related biomechanical changes. Finally, this study used a cross-sectional design, which captures a snapshot of the participants' current condition but does not allow for the assessment of changes over time or the establishment of causal relationships. This limitation restricts our ability to explore the progression of frailty and its long-term impact on lower limb biomechanics and overall physical function.

Conclusion and implications

Our study demonstrated that gait performance in older adults deteriorates as frailty progresses. Gait analysis, particularly through three-dimensional gait systems, has proven to be an effective tool for detecting frailty risk and facilitating the early identification and diagnosis of frailty in the older adults Clinically, it is crucial to assess gait performance, with a focus on the angles of the ankle and knee joints, as these parameters provide valuable insights into mobility and frailty. For older adults in pre-frail and frail states, interventions should prioritize improving balance and enhancing lower limb muscle strength to stabilize walking and reduce fall risk. Future research should focus on further investigating the structural and functional mechanisms that underlie gait kinematics in frail older adults, to better inform preventive and therapeutic strategies.

Data availability

The datasets used and/or analyzed during the current study available from the corresponding author on reasonable request.

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Author contributions
JC, L-ZH: Study concept and design. L-XL, T-XL: Acquisition of data. L-XL, S-QP, H-DB: Analysis and interpretation of data. JC, L-XL: Drafting of the manuscript. K-XH, L-ZH: Critical revision of the manuscript for important intellectual content. All authors have read and approved the final version of the manuscript.

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Declarations

Competing interests
The authors declare no competing interests.

Ethics approval and consent to participate
The study was approved by the ethics committee of our institution and complied with the World Medical Association Declaration of Helsinki. The study was performed from August 2023 to February 2024, and it was registered at the Chinese Clinical Trial Registry Network (ChiCTR2300073905).

Additional information
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