BMC Nephrology

RESEARCH

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Gender-specific sarcopenia screening in hemodialysis: insights from lower limb strength and physiological indicators

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Abstract

Objective Maintenance hemodialysis (MHD) patients often suffer from sarcopenia, affecting lower limb muscle strength and increasing the risk of falls and mortality. This study aims to develop an auxiliary screening model for sarcopenia in MHD patients based on machine learning methods, utilizing lower limb muscle strength indicators, while paying attention to the gender difference and exploring its value in sarcopenia screening.

Methods This cross-sectional study collected data from MHD patients at a hemodialysis center in China. Sarcopenia was assessed using the 2019 Asian Working Group for Sarcopenia update. A self-developed lower limb muscle strength testing device was used. Other physiological indicators, including basic information and lab findings, were collected. Participants were grouped into sarcopenia and control groups, with gender-specific binary classification models developed. Stratified shuffling and synthetic minority oversampling techniques were used to build screening classifiers.

Results Data from 164 MHD patients were ultimately collected, including 83 males (41 with possible sarcopenia or sarcopenia) and 81 females (53 with possible sarcopenia or sarcopenia). Gender-specific binary classification models were developed using lower limb muscle strength indicators, with the male model having an AUC of 79% and the female model an AUC of 80%, respectively. Combining lower limb muscle strength with other physiological indicators improved the female model's screening capability, achieving an AUC of 90%.

Conclusion This study demonstrates that the auxiliary screening model for sarcopenia, developed using machine learning methods, highlights the significant value of lower limb muscle strength indicators in identifying sarcopenia in MHD patients. The gender-specific screening models show good discriminatory ability across different genders, providing effective tools for the early screening and management of sarcopenia in MHD patients.

Trial registration Chinese Clinical Trial Registry (ChiCTR2100051111), registered on 2021–09–13.

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Keywords Maintenance hemodialysis, Sarcopenia, Machine learning, Identification, Lower limb muscle strength

Background

End-stage kidney disease (ESKD) is a global health challenge that continues to garner increasing attention. Hemodialysis remains the primary renal replacement therapy for 62.7% of ESKD patients [1]. However, this treatment is often associated with complications such as protein loss, metabolic acidosis, inflammation, and nutritional deficiencies, rendering maintenance hemodialysis (MHD) patients particularly vulnerable to sarcopenia [2, 3]. Sarcopenia, characterized by progressive and generalized loss of skeletal muscle mass and function, presents clinically as reduced muscle mass, decreased strength, and impaired physical function. Initially defined in the elderly [4, 5], sarcopenia in MHD patients differs due to the multifaceted impact of chronic kidney disease (CKD).

Unlike age-related sarcopenia, sarcopenia in MHD patients is exacerbated by the underlying disease complexities. Reported prevalence among MHD patients ranges from 9 to 37%, influenced by diagnostic criteria, socioeconomic factors, and lifestyle differences [6–10]. This variability is significant, as sarcopenia is closely linked to adverse outcomes, including increased mortality, cardiovascular events, and elevated healthcare costs [11]. The variability in prevalence highlights the necessity of tailored diagnostic and therapeutic strategies, particularly in light of differing MHD severities and diagnostic methods [12].

Muscle strength is a pivotal component of sarcopenia assessment, with handgrip strength (HGS) widely recommended as a diagnostic measure. However, lower-limb muscle weakness, rather than upper-limb strength, has a greater impact on functional capacity and fall risk [13, 14]. While handgrip strength is often used as a surrogate marker of overall muscle strength, evidence shows inconsistent correlations between handgrip strength and lower-limb strength across studies [15, 16]. This underscores the importance of directly evaluating lower-limb strength in sarcopenia assessment.

Although isokinetic dynamometers are commonly used to measure lower-limb strength, their high cost, lack of portability, and unsuitability for patients with joint disorders limit their clinical utility. In sarcopenia diagnosis, functional tests such as the 6-meter walking speed, the Five-Times-Sit-to-Stand Test (FTSST), and the Short Physical Performance Battery (SPPB) include elements reflecting lower-limb strength. However, few studies have systematically explored the relationship between lower-limb strength and sarcopenia, and limited research has investigated sarcopenia screening based on lower-limb strength.

This study assumes that lower-limb joint strength, such as knee, hip, and ankle joint strength in MHD patients is associated with sarcopenia status and can serve as a screening measure for sarcopenia screening. The novelty of this study lies in its focus on MHD patients, an understudied yet high-risk population for sarcopenia and its exploration of the specific relationship between lower-limb joint strength and sarcopenia. Besides, given that lower-limb muscles play a crucial role in gait and balance, they may serve as a more sensitive indicator of early sarcopenia compared to upper-limb strength like handgrip strength. Thus, this study integrates measurements from three major lower-limb joints to capture overall lower-limb function.

In previous work, we developed two simple, gender-specific sarcopenia screening tools for MHD patients using machine learning methods, which demonstrated robust performance, particularly in detecting possible sarcopenia cases [17]. Building on this foundation, the present study adopts the Asian Working Group for Sarcopenia (AWGS) 2019 consensus as the diagnostic criteria for sarcopenia [18]. A self-developed portable device was employed to measure the strength of three major lower-limb joints in MHD patients, aiming to evaluate the diagnostic utility of lower-limb strength in sarcopenia screening. By advancing innovative biomechanical diagnostic tools and establishing reference standards for sarcopenia in MHD patients, this study seeks to provide valuable insights for targeted lower-limb strength training, ultimately improving functional mobility and quality of life in this vulnerable population.

Methods

Study design and participants

This cross-sectional study enrolled patients living on MHD who visited to the Wenjiang Hemodialysis Center in the Department of Nephrology in West China Hospital, Sichuan University, Chengdu, China between September and December 2023. The inclusion criteria were (1) patients receiving MHD, (2) at least 12 weeks of MHD treatment (2–3 sessions/week) and plan to continue MHD treatment during the study period, and 3) ≥ 18 years of age. The exclusion criteria were (1) have skeletomuscular system deformity, (2) dyskinesia, (3) cardiac pacemakers/ICD installed, or (4) psychiatric disorders/single-leg amputation. Sarcopenia diagnosis was carried out via AWGS 2019 [18].

Ethical and legal considerations

This study received approval from the Ethics Committee (ethical approval number: 2023 [2063]) and was

performed in accordance with the principles of the Declaration of Helsinki. Written informed consent was obtained from all study participants and participants were informed that they could refuse to participate at any stage.

Comprehensive physiological indicators data collection

The collected data includes patients' basic information, body measurement results, and laboratory findings. Basic information was obtained from patients' medical archives, while body measurement results and laboratory findings were derived from the latest centralized examination at the hemodialysis center before data collection. HGS was measured using the arm without vascular access. Laboratory findings included routine blood examination, hepatic and renal function indicators, serum inorganic salts, and parathyroid hormone (PTH). Since urea and creatinine were measured again after hemodialysis, participants' urea and creatinine after hemodialysis were also collected.

Lower limb muscle strength test

In this study, a self-developed lower limb muscle strength testing device (see Fig. 1) was used. The measurement system of this lower limb muscle strength testing device consists of a detachable base and crossbar, five force dynamometers, two force display screens, and the corresponding wires and software. It can be used to measure the hip joint extension force, knee joint extension force, and ankle joint flexion force of the lower limbs. The test data can be directly read from the display screen or exported as a CSV file. The device has undergone rigorous evaluation by the Assistive Devices Quality Inspection Center of the Rehabilitation Assistive Devices Technical Service Center in Sichuan Province, China, and has obtained an official test report (Report No.: WT2022000051), confirming its reliability and applicability in lower limb muscle strength assessment [19].

Before each test, the testing environment was carefully prepared to ensure accuracy and consistency. The lower limb muscle strength testing device was placed on a horizontal surface without any objects underneath it. A chair without wheels and tilt was selected and positioned on the base of the testing device to prevent movement during the test. The force meter was then connected to the display screen, manually checked, and secured, with the instrument zeroed to confirm it was functioning correctly. To ensure measurement reproducibility, the force dynamometerss were calibrated using standard weights, with an acceptable error range controlled within ± 2%. All assessors underwent a consistency assessment and were only allowed to conduct tests if their operational coefficient of variation (CV) was < 5%. All participants were asked to seat in a standardized posture, and uniform testing movements were maintained throughout the process.

After the preparation, the participant sits on the chair and performs three types of joint strength tests according to the following steps:

1) Hip joint extension force test: The participant sits upright, places the upper part of the thigh close to the knee joint against the force meter, gradually lifts the thigh with increasing force, presses against the force meter with maximum strength, maintains the force steadily, and then slowly lowers the thigh after the data is recorded by the experimenter.
2) Knee joint extension force test: The participant sits upright, places the front part of the lower leg near

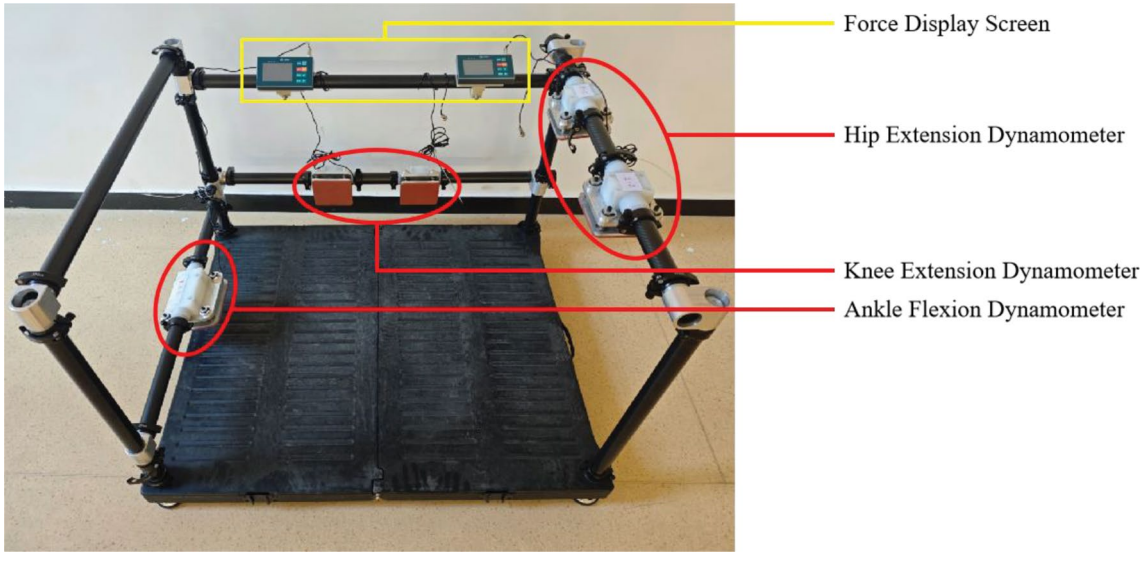

Fig. 1 A photograph of the lower limb muscle strength testing device

the ankle joint against the force meter, gradually extends the lower leg with increasing force, presses against the force meter with maximum strength, maintains the force steadily, and then slowly retracts the lower leg after recording the data.

3) Ankle joint flexion force test: The participant sits upright, places the heel on the base, presses the ball of the foot against the force meter, gradually lifts the forefoot with increasing force, presses against the force meter with maximum strength, maintains the force steadily, and then slowly lowers the forefoot after recording the data.

The schematic diagrams of three lower-limb joint strength measurements are shown in Fig. 2. After each joint strength test, the participant rests for 30 s. The experimenter adjusts the chair position to prepare for the next test. Each joint strength measurement is taken twice and the average results are calculated. During the test process, abnormal data were identified based on real-time force dynamometers readings. If a participant reported exerting maximal effort but the recorded force was below 10 N, or if the measured force exceeded the sensor's upper limit of 200 N, the test was repeated to ensure data reliability. If an accident occurs, the test is immediately terminated. Meanwhile, before the formal test, a pre-experiment is conducted to confirm the availability of the instruments, and the standard procedure is explained to all participants to ensure compliance.

Grouping and statistical analysis

Similar to Hassler's work [20], this study amalgamates MHD patients' exhibiting varying degrees of sarcopenia into a single sarcopenia group, encompassing possible sarcopenia, sarcopenia, and severe sarcopenia. Conversely, patients devoid of sarcopenia constitute the control group. This methodology is designed to construct a binary classifier, facilitating the discernment of sarcopenia in newly MHD patients. The integration of these groups not only streamlines the model but also diminishes the requisite data volume, thereby augmenting the model's screening efficacy.

Statistical analysis was performed using SPSS 26.0 software (IBM Corp., Armonk, N.Y., USA). The normality of continuous data was assessed using the Shapiro-Wilk test. For normally distributed data, values are presented as mean ± standard deviation (SD), while non-normally distributed data are presented as median (Q1, Q3). Categorical variables are presented as frequency (N) and percentage (%). Independent t-tests and Mann-Whitney U tests were used to compare lower limb muscle strength between the control and sarcopenia groups. Descriptive statistics were employed to summarize the data, and statistical significance was set at $p < 0.05$.

Consider that some patients may be unable to complete certain test postures due to pain or other reasons,, resulting in missing values. Thus, this study extrapolated missing values from the existing data to maximize the retention of potentially informative content. For instances with a single missing value within a feature, comparable instances with matching gender and sarcopenia status were identified. The missing values were then interpolated using the mean of the corresponding feature from instances without missing values in the selected group. After interpolation, the data format was standardized to reflect the original structure. All textual outcomes were converted into numerical categorical values to facilitate further analysis. Sarcopenia cases were denoted as "1" while control cases were labeled as "0".

To address the mild class imbalance in the original dataset, the Synthetic Minority Over-sampling Technique was applied only to the training set. This approach was adopted to synthesize samples of the minority class, and it would not significantly alter the true prevalence rate in the original dataset.

To ensure an adequate sample size for machine learning modeling, a power analysis based on the Hanley & McNeil formula for AUC-based studies was conducted. With an expected AUC of 0.8, $\alpha = 0.05$, and power ≥ 80%, the theoretical minimum sample size was 20. Furthermore, considering a maximum of four covariate

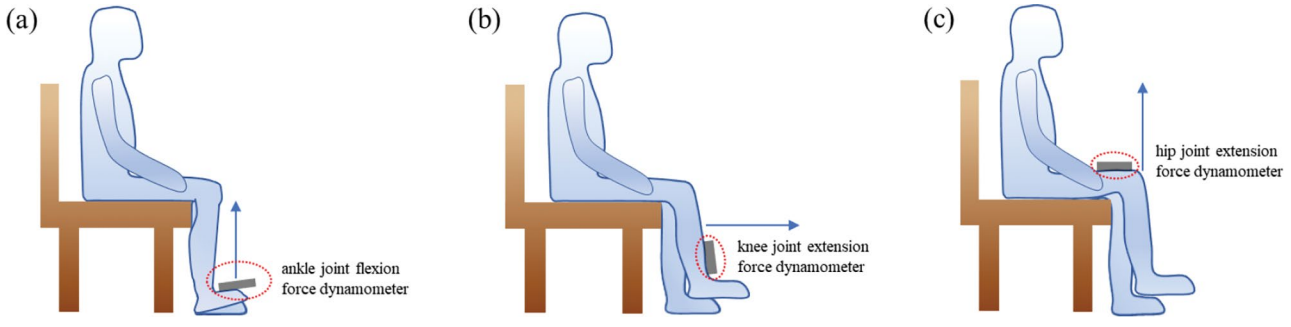

Fig. 2 Schematic diagrams of three lower-limb joint strength measurements. (**a**) ankle joint flexion force measurement; (**b**) knee joint extension force measurement; (**c**) hip joint extension force measurement

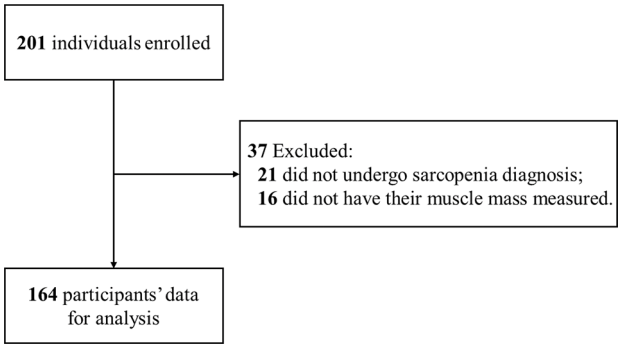

Fig. 3 The flow chart of the number of participants enrolled and excluded in this study

Table 1 Statistical analysis results of basic characteristics of study group

Characteristics	Control group	Sarcopenia group	*P*
Sex, N (%)	70 (100.00%)	94 (100.00%)	0.078
Male	41 (58.57%)	42 (44.68%)	
Female	29 (41.43%)	52 (55.32%)	
Age, mean ± SD			
Mixed-gender group	47.70 ± 9.79	60.35 ± 12.72	< 0.001
Male group	49.00 ± 10.46	61.33 ± 12.99	< 0.001
Female group	45.86 ± 8.59	59.56 ± 12.56	< 0.001
Height (cm), mean ± SD			
Mixed-gender group	164.07 ± 8.22	160.21 ± 8.11	0.003
Male group	168.95 ± 6.25	166.50 ± 6.62	0.087
Female group	157.17 ± 5.16	155.13 ± 5.09	0.089
Weight (kg), mean ± SD			
Mixed-gender group	62.35 ± 10.41	57.80 ± 11.30	0.009
Male group	66.80 ± 8.93	65.35 ± 9.52	0.477
Female group	56.07 ± 9.14	51.71 ± 8.67	0.036

SD: Standard deviation

adjustments in the models, the adjusted minimum sample size requirement was 40. This study included 164 MHD patients, exceeding the required threshold and ensuring sufficient statistical power (≥ 80%).

Feature selection and model development

Feature importance was determined using both the ranking of importance scores and the absolute values of the Lasso regression weights. The top features were selected based on their average ranking across these two metrics. Feature importance calculation and lasso regression programs were all performed via Python 3.

To assess the utility of lower limb muscle strength indicators in the auxiliary screening of sarcopenia among MHD patients, the methodology employed in this study mirrors that utilized in our previous study [17]. Throughout the model's developmental phase, this study adhered to the application of ten prevalent binary classification machine learning algorithms, encompassing K-Nearest Neighbor (KNN), Naive Bayes (NB), Logistic Regression (LR), Support Vector Machine (SVM), Multi-layer Perceptron (MLP), and an array of tree-based methodologies: Decision Tree (DT), Random Forest (RF), Adaptive Boosting (AdaBoost), Gradient Boosting Decision Tree (GBDT), and Light Gradient Boosting Machine (LGBM). The execution of these machine learning model development protocols was facilitated through the utilization of Python 3, with algorithm implementations drawn from the sklearn and lightgbm libraries.

Results

This study recruited 201 MHD patients, among whom 21 did not undergo sarcopenia diagnosis, and 16 did not take muscle mass testing. Ultimately, a total of 164 patients who completed the lower limb joint strength test and the sarcopenia diagnosis were included in this study (see Fig. 3). The basic characteristics of patients are presented in Table 1. The original dataset of lower-limb muscle strength indicators contains a total of seven features (including gender, excluding the sarcopenia diagnosis result). And there were totaling 2 missing values (0.17%) in two features of two samples. In addition, there were no missing values in the comprehensive physiological indicator data of the 164 patients included.

Table 2 reports the descriptive statistical analysis data of the lower limb muscle strength indicators of male and female MHD patients, stratified according to the sarcopenia group and control group. Unadjusted statistical analysis found that the differences in all 6 lower limb muscle strength indicators of male MHD patients between these two groups were statistically significant, and the muscle strength of each lower limb joint in the male sarcopenia group was less than that in the control group. For female MHD patients, except for the right knee joint extension force, the differences in the other 5 lower limb muscle strength indicators between these two groups were statistically significant.

After calculating the feature importance values and absolute weights of lasso regression of 6 lower limb muscle strength indicators, the average ranking was gotten. The ranking results of features in two sex groups shown in Table 3 were in descending order.

We used the combination of the top 2 to the top 6 (all) features in Table 3 for modeling. Through the horizontal comparison of the performance of the developed models, we aimed to find the optimal set of lower limb muscle strength indicators for assisting in the screening of sarcopenia in MHD patients of different genders. After discarding the models that showed overfitting or underfitting, Table 4 presents the evaluation results of each voting classifier for male MHD patients established using the top 2 to the top 6 (all) features. The sensitivity, specificity, F1 score, and AUC of each voting classifier using these 5 feature sets were plotted in a boxplot

Table 2 Statistical analysis results of lower limb muscle strength indicators between sarcopenia and control groups of different genders

Features	Male		*P*	Female		*P*
	Control group (*N* = 42)	Sarcopenia group (*N* = 41)		Control group (*N* = 28)	Sarcopenia group (*N* = 53)	
Hip joint extension force of left leg	113.44(75.94, 140.54)	85.94(48.75, 118.69)	0.008[2]	75.90(53.82, 107.28)	44.92(31.39, 67.96)	< 0.001[2]
Hip joint extension force of right leg	120.56(93.02, 162.80)	92.97(63.17, 126.72)	0.005[2]	88.85(63.13, 120.52)	54.66(38.27, 80.97)	< 0.001[2]
Knee joint extension force of left leg	97.43(70.49, 113.20)	73.50(55.85, 97.92)	0.011[2]	61.97(47.70, 86.07)	53.34(38.31, 70.16)	0.018[2]
Knee joint extension force of right leg	108.65 ± 33.17	84.79 ± 37.77	0.003[1]	64.32(55.08, 109.00)	58.71(37.69, 84.54)	0.073[2]
Ankle joint flexion force of left leg	122.62(92.98, 169.94)	90.03(70.92, 108.27)	< 0.001[2]	80.70(46.05, 99.05)	44.92(32.38, 75.50)	0.001[2]
Ankle joint flexion force of right leg	125.15 ± 52.91	93.67 ± 42.76	0.004[1]	78.01(38.27, 117.19)	49.78(31.71, 68.86)	0.008[2]

[1] Values are presented as mean ± standard deviation (SD), P-values are calculated using the t-test for normally distributed variables

[2] Values are presented as median (P25, P75), P-values are calculated using the Mann-Whitney U test for non-normally distributed variables

Table 3 Lower limb strength indicators ranked by the average ranking of feature importance and absolute feature weight of Lasso regression about males and females

Feature	IRF	RIFI	AFWL	RAFWL	AR	*P*
Male						
Ankle joint flexion force of left leg	0.2147	1	1.0255	2	1.5	< 0.001
Hip joint extension force of right leg	0.1761	3	1.2222	1	2	0.005
Knee joint extension force of right leg	0.1831	2	0.7934	4	3	0.003
Hip joint extension force of left leg	0.1363	5	0.7948	3	4	0.008
Ankle joint flexion force of right leg	0.1607	4	0.2726	5	4.5	0.004
Knee joint extension force of left leg	0.1292	6	0.2166	6	6	0.011
Female						
Hip joint extension force of left leg	0.2054	1	0.8752	1	1	< 0.001
Ankle joint flexion force of left leg	0.1592	4	0.5104	2	3	0.001
Ankle joint flexion force of right leg	0.1937	2	0	5	3.5	0.008
Hip joint extension force of right leg	0.1878	3	0	5	4	< 0.001
Knee joint extension force of left leg	0.1283	5	0.1332	3	4	0.018
Knee joint extension force of right leg	0.1257	6	0.1188	4	5	0.073

IRF: importance value calculated by random forest, RIRF: ranking of importance value calculated by random forest, AFWL: absolute feature weight of lasso regression, RAFWL: ranking of absolute feature weight of lasso regression, AR: average ranking

Table 4 The voting classifier's evaluation metrics (%) about 5 feature sets of male MHD patients

Metric	Top 2 features	Top 3 features	Top 4 features	Top 5 features	All features
ACCTRS	72.58 ± 2.66	71.97 ± 3.47	71.97 ± 3.12	72.73 ± 3.39	72.12 ± 2.97
ACCTES	76.47 ± 11.76	74.71 ± 10.86	72.94 ± 13.21	74.71 ± 12.63	70.59 ± 10.85
AVAD	10.97 ± 10.13	11.27 ± 8.58	12.56 ± 9.75	12.42 ± 10.13	11.23 ± 7.38
Precision	71.45 ± 12.04	70.34 ± 11.61	70.13 ± 14.11	72.30 ± 15.00	67.89 ± 12.36
Sensitivity	87.50 ± 12.50	85.00 ± 12.25	78.75 ± 16.82	81.25 ± 12.81	78.75 ± 15.86
Specificity	66.67 ± 17.92	65.56 ± 18.22	67.78 ± 18.89	68.89 ± 20.37	63.33 ± 20.52
F1 Score	78.06 ± 10.21	76.20 ± 9.36	73.22 ± 12.80	75.59 ± 11.14	71.53 ± 9.85
AUC	79.03 ± 13.88	79.86 ± 15.44	78.47 ± 16.51	79.03 ± 15.84	77.78 ± 14.82

ACCTRS: accuracy of training set, ACCTES: accuracy of test set, AVAD: absolute value of accuracy difference between training set and test set, AUC: the area under the receiver operating characteristic curve

as shown in Fig. 4. The results indicate that the voting classifier using the top 2 features (ankle joint flexion force and right hip joint extension force of left leg), had the highest average sensitivity and F1 score, making the top 2 features become the most suitable lower limb muscle strength indicators for assisting in the screening of sarcopenia in male MHD patients. The comprehensive average approximate ROC curve of the voting classifier and the other two machine learning classifiers it combined using the top 2 lower limb muscle strength indicators after feature selection and ranking for male MHD patients are shown in Fig. 5.

After discarding models that exhibited overfitting or underfitting, Table 5 presents the evaluation results of each voting classifier for female MHD patients developed using the top 2 to the top 6 (all) features. The sensitivity, specificity, F1 score, and AUC of each voting classifier using these 5 feature sets were also plotted as a boxplot

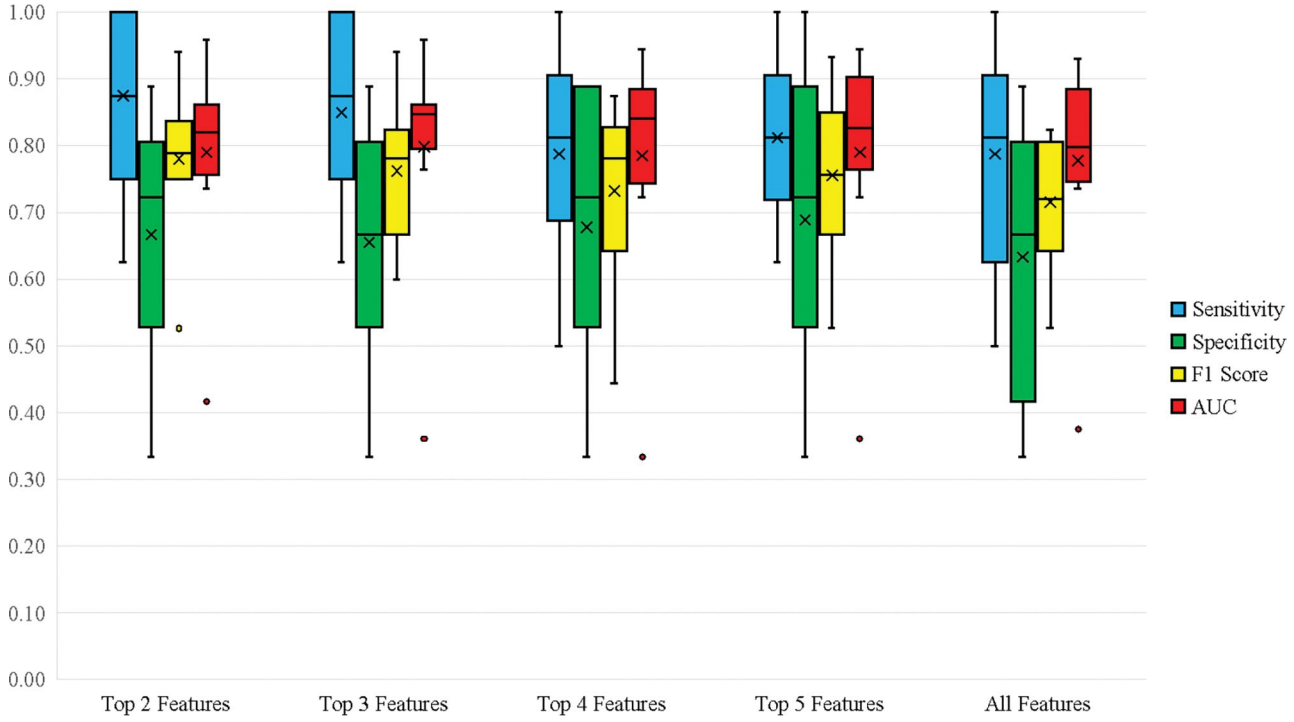

Fig. 4 The boxplot of evaluation results for each voting classifier using 5 lower limb muscle strength feature sets after feature selection of male MHD patients

shown in Fig. 6. The results indicate that the top 4 features (hip joint extension force and ankle joint flexion force of both legs) are the optimal lower limb muscle strength indicators for assisting in the screening of sarcopenia in female MHD patients. At this time, the comprehensive average approximate ROC curve of the voting classifier and the other two machine learning classifiers it combined using the top 4 lower limb muscle strength indicators after feature selection and ranking for female MHD patients is shown in Fig. 7.

The results of using various kinds of lower limb joint muscle strength indicators combined with gender characteristics

This study also explored the contribution of various kinds of lower limb joint strength to the assisted screening of sarcopenia, rather than investigating whether the muscle strength of the left or right leg contributes more. Therefore, in this study, for male and female MHD patients, only the hip joint extension force, knee joint extension force, or ankle joint flexion force of both legs were included to develop assisted screening models. The three resulting models were compared horizontally with the model using the optimal set of lower limb muscle strength indicators. Table 6 reports the evaluation results of voting classifiers after modeling with different lower limb joint strengths and the optimal set of lower limb muscle strength indicators of different genders. The results indicate that using the optimal set of lower limb muscle strength indicators selected through feature selection performs better than using any single joint strength, which is similar to how a voting classifier combines several individual classifiers to improve its classification performance.

The results of using optimal comprehensive physiological indicators combined with lower limb muscle strength indicators

Moreover, this study further explored the machine learning assisted screening effects using the optimal comprehensive physiological indicators combined with lower limb muscle strength indicators. According to our previous research, the indicators for male patients include age, fasting blood glucose, and parathyroid hormone [17], as well as ankle joint flexion force of left leg and hip joint extension force of right leg; the indicators for female patients include age, grip strength, total bilirubin, and post-dialysis creatinine [17], as well as hip joint extension force and ankle joint flexion force of both legs. Machine learning models were developed and evaluated using the same methods. The evaluation results of the screening models and their comparison with the use of each optimal feature set al.one are presented in Table 7.

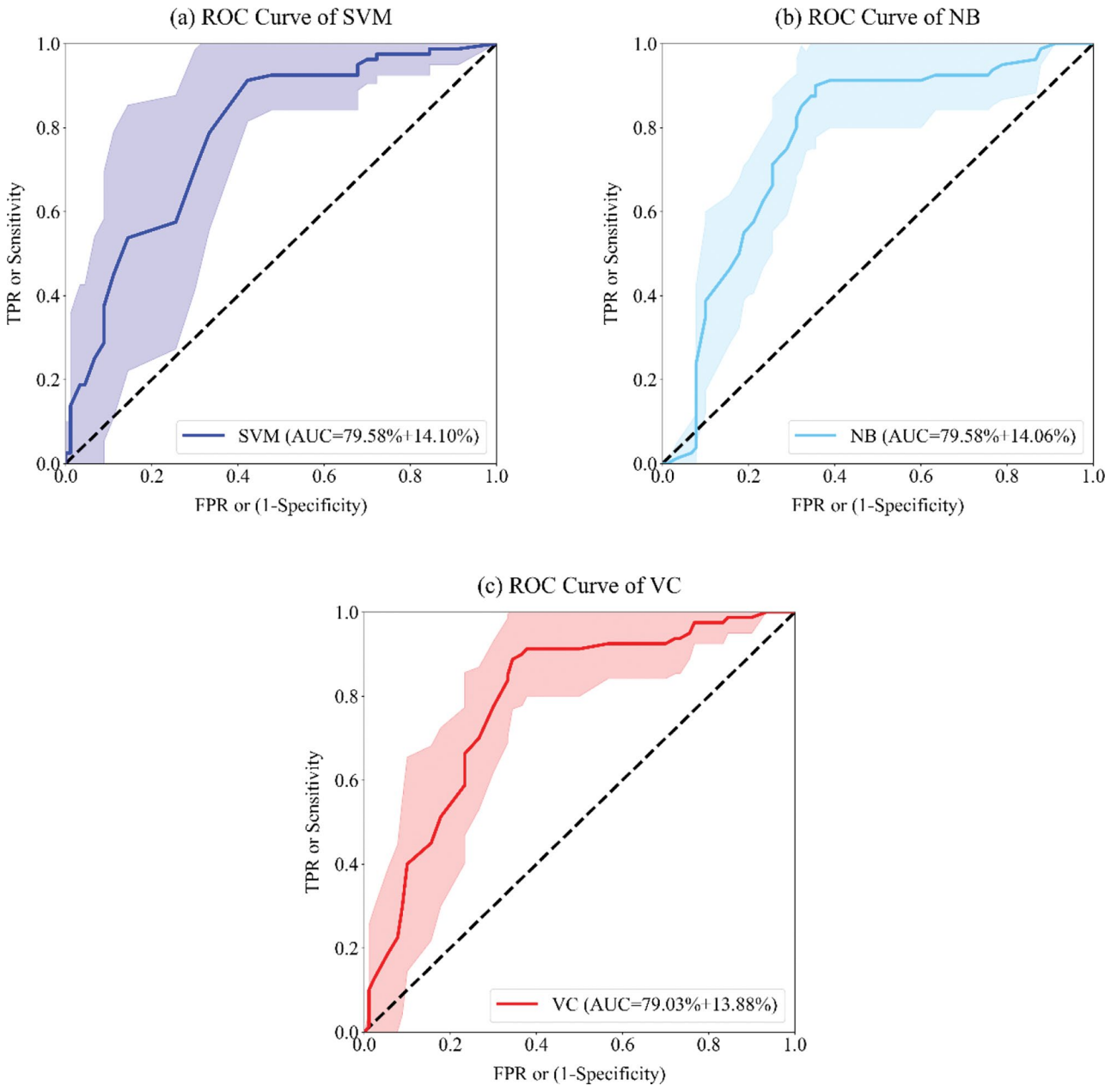

Fig. 5 Combined average approximate ROC curves of voting classifier and other two classifiers it combined using the top 2 lower limb muscle strength indicators after feature selection of male MHD patients. (**a**) ROC curve of SVM model; (**b**) ROC curve of NB model; (**c**) ROC curve of VC model

Table 5 The voting classifier's evaluation metrics (%) about 5 feature sets of female MHD patients

Metric	Top 2 features	Top 3 features	Top 4 features	Top 5 features	All features
ACCTRS	72.14 ± 4.13	67.14 ± 4.13	73.69 ± 3.26	72.14 ± 5.06	71.19 ± 2.86
ACCTES	70.00 ± 9.28	71.18 ± 7.18	74.71 ± 9.86	71.76 ± 9.04	71.76 ± 8.65
AVAD	10.34 ± 7.95	8.53 ± 4.28	9.67 ± 6.18	11.33 ± 4.91	8.66 ± 5.10
Precision	82.21 ± 10.75	81.63 ± 7.30	87.40 ± 9.86	81.78 ± 8.87	82.92 ± 8.41
Sensitivity	70.91 ± 12.06	73.64 ± 16.49	72.73 ± 14.08	74.55 ± 16.16	71.82 ± 11.82
Specificity	68.33 ± 21.67	66.67 ± 14.91	78.33 ± 18.33	66.67 ± 18.26	71.67 ± 15.00
F1 Score	75.03 ± 8.08	75.72 ± 9.37	78.26 ± 9.29	76.54 ± 9.14	76.36 ± 7.65
AUC	78.18 ± 12.20	80.00 ± 11.55	80.45 ± 13.18	79.39 ± 12.77	77.42 ± 14.09

ACCTRS: accuracy of training set, ACCTES: accuracy of test set, AVAD: absolute value of accuracy difference between training set and test set, AUC: the area under the receiver operating characteristic curve

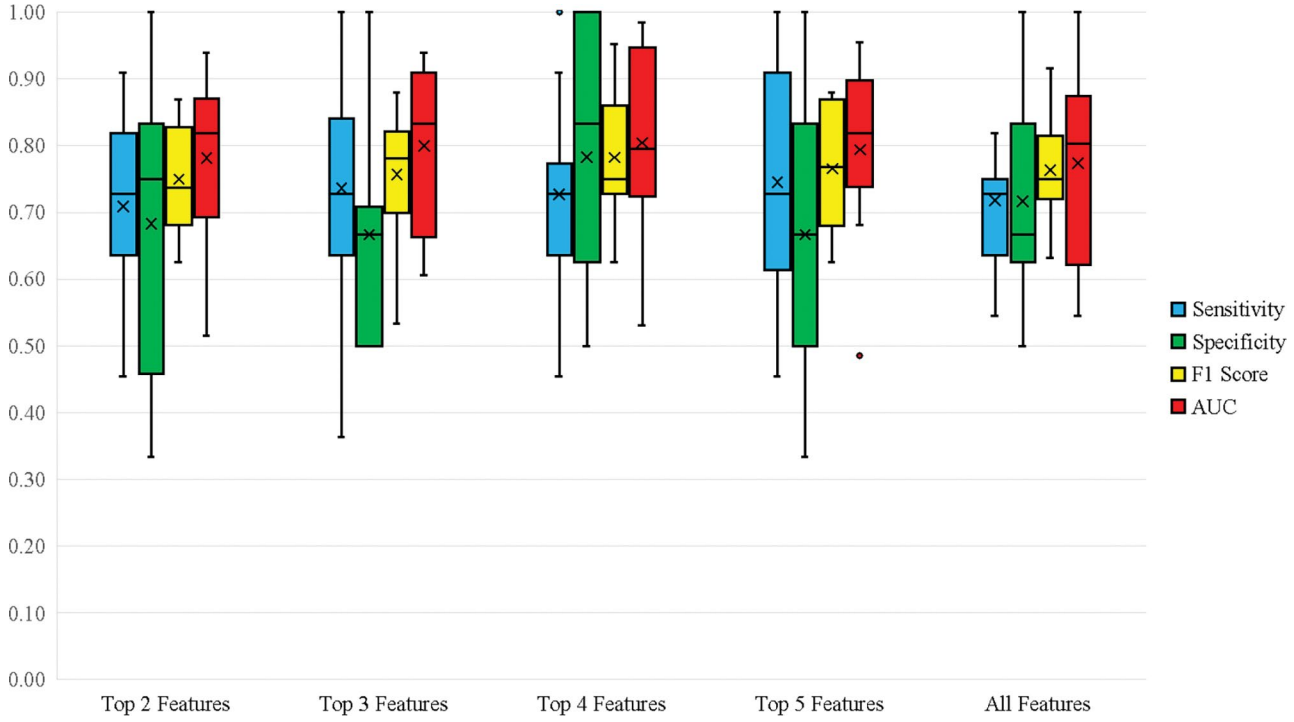

Fig. 6 The boxplot of evaluation results for each voting classifier using 5 lower limb muscle strength feature sets after feature selection of female MHD patients

Discussion

This study investigates the relationship between sarcopenia and lower limb muscle strength in MHD patients, emphasizing the clinical relevance of gender-specific screening models for sarcopenia. We chose to measure the raw data for both the left and right lower limbs separately, instead of using the average for capturing individual differences among patients more comprehensively. It can help avoid the loss of important details in the biomechanical information related to sarcopenia. The results demonstrate a clear association between lower limb muscle strength and sarcopenia, with male MHD patients in the sarcopenia group exhibiting significantly lower muscle strength compared to the control group. For female MHD patients, although the right knee joint extension force was the only measure not significantly reduced, overall lower limb muscle strength was still compromised, indicating widespread impairment. These findings underscore the importance of assessing lower limb muscle strength in sarcopenia diagnosis and management, highlighting distinct gender differences that should be considered in clinical practice. Existing literature suggests that maximal isokinetic leg extension strength in adult males declines at a rate of approximately 0.8–1.0% annually, with a more accelerated decline after the age of 52 [21]. This parameter is crucial for maintaining independence in daily activities, and leg extension strength has been linked to slower walking speeds, which makes it an important metric for detecting muscle weakness in older adults [22]. Studies on elderly stroke patients have similarly revealed a negative correlation between sarcopenia and lower-limb strength [23], and the relative strength of the left and right legs has been associated with balance control, indicating its role in postural stability [24]. These findings further reinforce the clinical value of lower-limb strength assessments as a key component in the diagnosis and management of sarcopenia, particularly in MHD patients.

This study developed models for the assisted screening of sarcopenia in MHD patients based on gender. The model for males used only 2 lower limb muscle strength indicators (left ankle joint flexion force and right hip joint extension force) and achieved a high sensitivity level. Although the specificity was relatively low, it still indicates that the model focuses more on correctly classifying patients with sarcopenia. The model for females used 4 lower limb muscle strength indicators (left and right hip joint extension force, left and right ankle joint flexion force) and improved the average precision and specificity without reducing sensitivity. The F1 scores and AUC levels of the models for males and females were relatively similar. The study suggests that when using lower limb muscle strength indicators for the assisted screening of sarcopenia in MHD patients, different lower limb muscle strength indicators and classifiers should be used for different genders to achieve more accurate results.

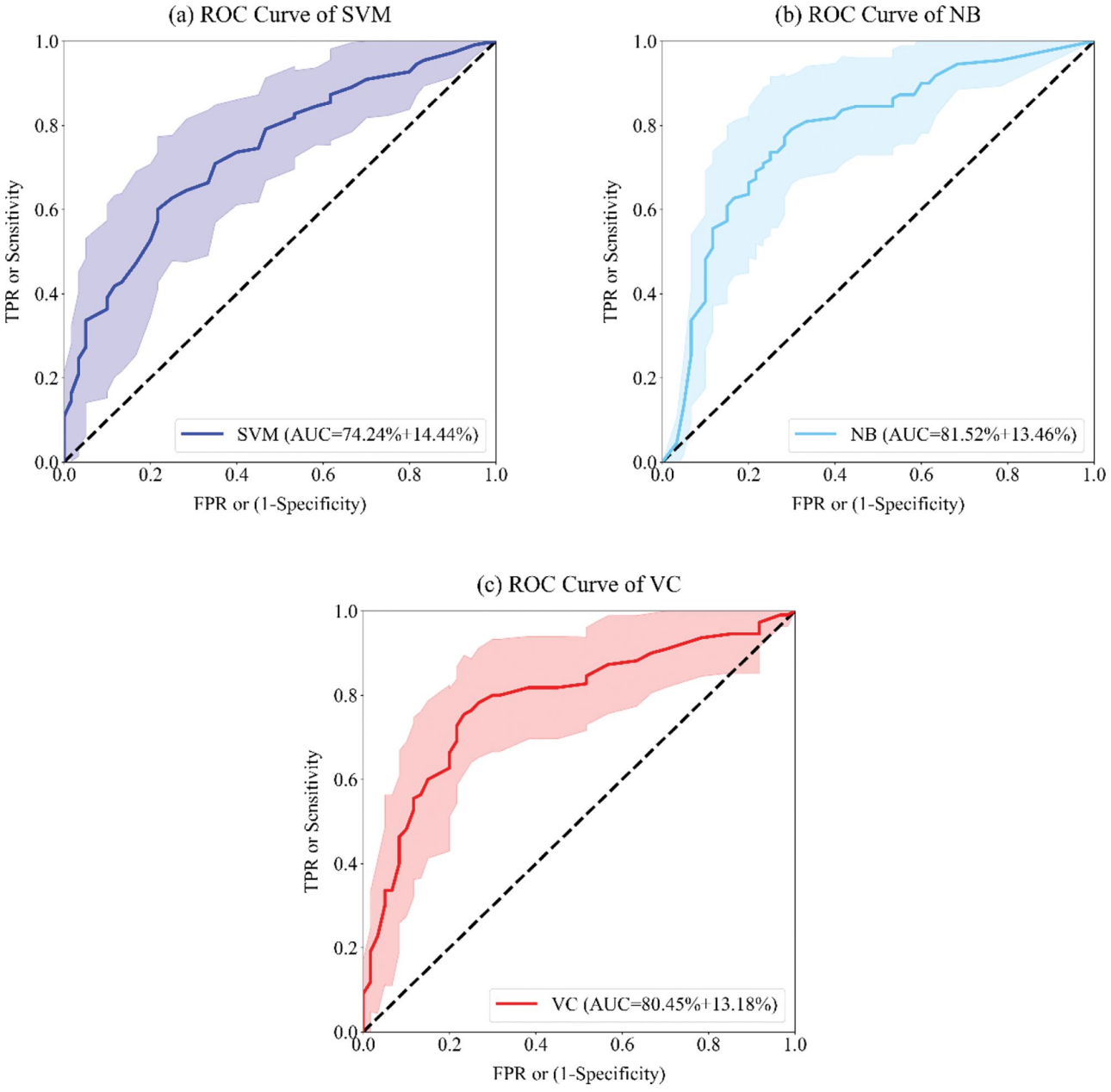

Fig. 7 Combined average approximate ROC curves of voting classifier and other two classifiers it combined using the top 4 lower limb muscle strength indicators after feature selection of female MHD patients. (**a**) ROC curve of SVM model; (**b**) ROC curve of NB model; (**c**) ROC curve of VC model

When comparing the classification effects of individual joint strength measures, hip joint extension strength was the least effective for males, while knee joint extension strength performed worst for females. However, classification models using a combination of optimal lower-limb strength indicators consistently outperformed those relying on single joint measurements. This finding aligns with existing research, which suggests that sarcopenia patients with chronic stroke exhibit reduced knee joint extension and ankle joint flexion strength due to atrophy of muscles such as the quadriceps and gastrocnemius [25]. Knee joint extension strength has also been linked to lean body mass index and sarcopenia diagnosis [26]. Although studies on hip joint strength are limited, evidence suggests that sarcopenia patients often exhibit reduced bone density and quadriceps strength, potentially impacting hip joint strength [27]. Interestingly, in this study, knee joint extension strength was identified as a less reliable indicator for MHD patients, suggesting that the unique characteristics of this population may require further exploration. The inclusion of knee joint extension strength negatively impacted model performance, which

Table 6 The voting classifier's evaluation metrics (%) using different lower limb joint strengths and the optimal set of lower limb muscle strength indicators of different genders

Features used	Hip joint extension force of both legs	Knee joint extension force of both legs	Ankle joint flexion force of both legs	Ankle joint flexion force of left leg and hip joint extension force of right leg
Male				
ACCTRS	62.27 ± 3.42	65.00 ± 2.83	69.55 ± 2.29	72.58 ± 2.66
ACCTES	60.59 ± 11.48	67.65 ± 11.54	70.00 ± 8.50	76.47 ± 11.76
AVAD	12.06 ± 8.74	12.27 ± 7.45	8.62 ± 5.98	10.97 ± 10.13
Precision	58.06 ± 13.08	66.85 ± 12.62	69.88 ± 10.62	71.45 ± 12.04
Sensitivity	65.00 ± 20.00	63.75 ± 19.72	67.50 ± 12.75	87.50 ± 12.50
Specificity	56.67 ± 18.89	71.11 ± 15.87	72.22 ± 15.91	66.67 ± 17.92
F1 Score	59.99 ± 13.31	64.03 ± 14.07	67.80 ± 8.65	78.06 ± 10.21
AUC	70.56 ± 16.08	71.67 ± 12.41	71.94 ± 12.39	79.03 ± 13.88
Features used	**Hip joint extension force of both legs**	**Knee joint extension force of both legs**	**Ankle joint flexion force of both legs**	**Hip joint extension force and ankle joint flexion force of both legs**
Female				
ACCTRS	64.40 ± 3.55	52.62 ± 3.60	66.31 ± 3.01	73.69 ± 3.26
ACCTES	67.06 ± 11.53	60.00 ± 8.65	71.18 ± 9.65	74.71 ± 9.86
AVAD	12.47 ± 8.05	11.06 ± 7.72	10.46 ± 7.15	9.67 ± 6.18
Precision	77.67 ± 8.44	73.14 ± 8.69	81.11 ± 10.26	87.40 ± 9.86
Sensitivity	70.00 ± 16.79	61.82 ± 13.97	73.64 ± 14.35	72.73 ± 14.08
Specificity	61.67 ± 19.79	56.67 ± 20.00	66.67 ± 18.26	78.33 ± 18.33
F1 Score	72.44 ± 11.34	66.05 ± 8.97	76.25 ± 9.25	78.26 ± 9.29
AUC	77.12 ± 16.69	67.88 ± 10.29	74.39 ± 13.88	80.45 ± 13.18

ACCTRS: accuracy of training set, ACCTES: accuracy of test set, AVAD: absolute value of accuracy difference between training set and test set, AUC: the area under the receiver operating characteristic curve

could be attributed to data limitations or specific physiological factors in the MHD population. Further studies incorporating numerical simulations of the musculoskeletal system are warranted to better understand the biological mechanisms that link sarcopenia to joint strength.

This study also further explored the machine learning assisted screening effect using optimal comprehensive physiological indicators combined with lower limb muscle strength indicators through the sarcopenia auxiliary screening model for MHD patients built in the preliminary study [17]. Finally, for male patients, optimal physiological indicators(age, fasting blood glucose, and parathyroid hormone)were sufficient for effective screening. In contrast, combining physiological and lower limb muscle strength indicators significantly enhanced the model's sensitivity and AUC for females, achieving an average sensitivity of 90%. These findings could have important implications for clinical practice, where tailored screening strategies might help prioritize interventions based on gender-specific profiles.

The sarcopenia assisted screening models for MHD patients based on lower limb joint strength proposed in this study exhibits the following advantages. (1) Traditional sarcopenia screening methods are primarily based on data from the general elderly population, with limited consideration of the unique characteristics of MHD patients, such as uremic toxin-induced muscle metabolism disorders and inflammation-driven muscle loss. Existing screening tools rarely focus on lower limb strength, which is crucial in this population due to prolonged sitting during dialysis sessions, contributing to proximal muscle atrophy. Our study addresses this gap by incorporating lower limb strength indicators, allowing for a more sensitive assessment of sarcopenia in MHD patients. (2) While the AWGS 2019 consensus recommends muscle mass and calf circumference measurements, these methods may be affected by fluid overload and bone metabolism abnormalities, limiting their reliability in MHD patients. By using a lower limb strength assessment, our model avoids these confounding factors and provides a more stable evaluation. (3) Conventional metrics such as handgrip strength, muscle mass, and calf circumference assess muscle quality or single-function performance, whereas lower limb strength is closely linked to mobility and fall risk, making it a more functionally relevant indicator in this population. (4) Compared to simple screening tools like calf circumference measurement [28], our machine learning-based integrative approach reduces operator dependency, requires less than five minutes per assessment, and generates

Table 7 The voting classifier's evaluation metrics (%) and comparison results using optimal comprehensive physiological indicators and lower limb muscle strength indicators for MHD patients of different genders

Features used	Age, fasting blood glucose, and parathyroid hormone	Ankle joint flexion force of left leg and hip joint extension force of right leg	Age, fasting blood glucose, parathyroid hormone, ankle joint flexion force of left leg and hip joint extension force of right leg
Male			
ACCTRS	86.59 ± 1.89	72.58 ± 2.66	78.79 ± 2.25
ACCTES	80.71 ± 4.29	76.47 ± 11.76	70.59 ± 10.85
AVAD	6.61 ± 3.63	10.97 ± 10.13	12.73 ± 8.41
Precision	79.28 ± 9.86	71.45 ± 12.04	65.67 ± 11.37
Sensitivity	77.50 ± 11.21	87.50 ± 12.50	81.25 ± 17.00
Specificity	83.12 ± 9.70	66.67 ± 17.92	61.11 ± 16.67
F1 Score	77.32 ± 5.36	78.06 ± 10.21	71.82 ± 12.12
AUC	87.40 ± 4.41	79.03 ± 13.88	81.53 ± 10.23
Features used	**Age, grip strength, total bilirubin, and post-dialysis creatinine**	**Hip joint extension force and ankle joint flexion force of both legs**	**Age, grip strength, total bilirubin, and post-dialysis creatinine, hip joint extension force and ankle joint flexion force of both legs**
Female			
ACCTRS	66.73 ± 4.28	73.69 ± 3.26	96.55 ± 1.35
ACCTES	74.29 ± 8.57	74.71 ± 9.86	87.06 ± 8.65
AVAD	12.72 ± 5.77	9.67 ± 6.18	10.68 ± 8.14
Precision	81.86 ± 7.58	87.40 ± 9.86	91.15 ± 9.79
Sensitivity	76.15 ± 13.95	72.73 ± 14.08	90.00 ± 8.58
Specificity	71.25 ± 15.86	78.33 ± 18.33	81.67 ± 20.34
F1 Score	78.04 ± 8.85	78.26 ± 9.29	90.06 ± 6.44
AUC	77.69 ± 7.92	80.45 ± 13.18	90.45 ± 5.94

ACCTRS: accuracy of training set, ACCTES: accuracy of test set, AVAD: absolute value of accuracy difference between training set and test set, AUC: the area under the receiver operating characteristic curve

automated risk scores, minimizing human error. (5) Our model eliminates the need for expensive muscle mass measurement devices, improving accessibility and cost-effectiveness, especially in resource-limited settings. Future research could focus on integrating this machine learning model into electronic health record systems in dialysis centers, enabling real-time risk assessment and personalized intervention recommendations.

Limitations

There are several limitations to this study. Firstly, the sample size was relatively small, and the study was cross-sectional, which may limit the generalizability of the findings. Moreover, to simplify the model, we combined the categories of possible sarcopenia, sarcopenia, and severe sarcopenia into a binary classification, which precluded a more nuanced analysis of sarcopenia severity. The reliance on the AWGS 2019 consensus for sarcopenia diagnosis may also restrict the model's applicability to populations using different diagnostic criteria. Although the self-developed lower-limb joint strength testing device used in this study has passed testing and certification by a rehabilitation assistive device quality inspection center, and all measurements were performed using standardized procedures, the device has not undergone independent validation across multiple centers or laboratories. This geographical limitation may introduce potential bias concerning the generalizability and reproducibility of the measurements, particularly in relation to different operators, clinical settings, or patient populations. We acknowledge that the absence of multi-center and multi-operator validation may limit the broader clinical applicability of this tool and poses a risk of measurement bias associated with non-validated equipment. Future research should involve larger, more diverse populations and explore the underlying physiological mechanisms through advanced modeling techniques, such as numerical simulations of the musculoskeletal system.

Conclusion

The results of this study underscore the significant value of lower limb muscle strength indicators in the assisted screening of sarcopenia, with gender-specific models offering superior performance. In clinical practice, a gender-tailored approach should be adopted for the early detection of sarcopenia, with male MHD patients benefiting from comprehensive physiological indicators alone, while female MHD patients requiring a

combined approach for more accurate screening. These findings provide a solid foundation for improving sarcopenia screening and management, with the potential for more personalized and effective interventions in MHD patients.

Acknowledgements
The authors would like to thank all of the healthcare providers and patients who participated in this study from Wenjiang Hemodialysis Center in the Department of Nephrology at West China Hospital, Sichuan University, Chengdu, China.We also extend our gratitude to all the funding agencies that supported this research.

Author contributions
Y.J.Y., H.L.L., P.F., J.R.Y., Y.C., and H.H.Y. prepared the manuscript, designed the study and organized the coordination. Y.J.Y., H.L.L., Y.C., and Y.Q. searched literatures. Y.J.Y., Y.C., and Y.Q. collected the data of MHD patients. H.L.L. and F.Y. analyzed the data. Y.J.Y. and H.L.L. are the major contributors in writing the manuscript. All authors read and approved the final manuscript.

Funding
This research was funded by the 1.3.5 project for disciplines of excellence from West China Hospital of Sichuan University (ZYGD23015), the Sichuan Province science and technology innovation base project (grant number: 2023ZYD0173), the Major Research Programs of the Science & Technology Department of Sichuan Province (grant number: 2022ZDZX0032), the National Natural Science Foundation of China (grant number: 12102072), and the Project of Sichuan Luzhou Science and Technology Bureau (grant number: 2022CDLZ-25), the Sichuan-Chongqing Science and Technology Innovation Cooperation Plan (grant number: 2024YFHZ0072).

Data availability
The data used in this study are not publicly available due to privacy and confidentiality concerns for the participants. The data contain sensitive personal information and have been collected in compliance with ethical guidelines to protect the privacy of the study participants. Data access may be provided upon reasonable request to the corresponding author, subject to approval by the relevant ethics committee and in accordance with the applicable data protection laws.

Declarations

Ethics approval and consent to participate
This study was approved by the biomedical ethics committee of the West China University of Sichuan University (ethical approval number: 2023 [2063]) and was performed in accordance with the principles of the Declaration of Helsinki. Written informed consent was obtained from all study participants and participants were informed that they could refuse to participate at any stage.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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Received: 17 February 2025 / Accepted: 12 May 2025
Published online: 19 May 2025

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