

Original Article

Muscle and Neuromuscular Function Indicators Associated with Comfortable and Maximum Gait Speed in Community-Dwelling Older Adults: An Exploratory Analysis Using Regression Tree and LASSO Regression

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Abstract

Objectives: To explore candidate muscle and neuromuscular function indicators associated with comfortable and maximum gait speed in older adults and to examine their hierarchical and complementary relationships using regression tree and least absolute shrinkage and selection operator (LASSO) regression. **Methods:** This cross-sectional study included 378 community-dwelling older adults (73.9 ± 5.3 years; 69.6% women) in the regression tree analysis. LASSO regression was based on complete-case data from 315 participants. Muscle and neuromuscular function was assessed using muscle mass, muscle strength, the five-times chair stand test (5-CST), and ground reaction force (GRF)- and rate of force development (RFD)-derived parameters obtained during a rapid heel-raising task. **Results:** Regression tree analysis selected the 5-CST for both comfortable and maximum gait speed. The maximum rate of force development (RFDmax) was additionally selected for both gait conditions, whereas grip strength was selected only for maximum gait speed. In the complete-case LASSO analysis, additional muscle strength- and force-related indicators, including knee extension strength and GRF-related parameters, were selected. The 5-CST and RFDmax were common in both analyses. **Conclusions:** Among relatively high-functioning community-dwelling older adults, gait speed appears to be associated not only with muscle strength but also with neuromuscular function, particularly the capacity to generate force rapidly.

Keywords: Chair Stand Test, Gait Speed, Neuromuscular Functions, Older Adult, Rate of Force Development

Introduction

Japan is a rapidly aging society, with individuals aged ≥ 65 years accounting for 29.4% of the total population in 2025¹. Extending healthy life expectancy has become a public health priority in this super-aged society.

Maintaining walking ability is essential to allow older adults to live independently in their community and sustain an active lifestyle². Among the various gait parameters used to assess walking ability, gait speed is considered a simple, reliable, and clinically meaningful marker of overall health status and functional capacity in older adults³. Slower gait speed is associated with a range of adverse outcomes, including falls⁴⁻⁶, restricted life-space mobility⁷, social isolation⁸, and progression to care dependency⁹, profoundly affecting the daily lives of older adults.

Aging is accompanied by a progressive decline in muscle and neuromuscular function, particularly in the lower limbs¹⁰⁻¹⁵. Notably, from a physiological perspective, declines in muscle power and rapid force development appear to occur earlier and to a greater extent than

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reductions in muscle mass or maximal strength with advancing age^{16–20}. While muscle strength represents the maximal force that a muscle can produce, muscle power or rapid force generation is essential for many functional tasks, including walking^{21–25}. Consistent with these physiological shifts, biomechanical studies have demonstrated that aging is associated with reductions in joint range of motion, joint moments, and power generation during walking, particularly in the ankle joint, which plays a critical role in propulsion^{26,27}. These combined neuromuscular and biomechanical alterations impair mobility and physical performance^{13,28}. Various indicators have been used to evaluate the muscle and neuromuscular functions associated with gait speed, including morphological factors such as skeletal muscle mass²⁹, muscle strength (e.g. grip³⁰, knee^{28,31}, and ankle strength³²), functional performance tests such as the five-times chair stand test (5-CST)^{33,34} and indices reflecting rapid force production capacity such as power³², ground reaction force (GRF), and rate of force development (RFD)^{35–39}. Although numerous studies have reported the effects of these age-related changes on gait, multiple factors, including muscle mass, strength, and power, interact in a complex manner and their relative contributions remain unclear. In addition, gait speed is affected not only by physical aspects, but also by sensory and psychological factors. A previous study using relative weight analysis demonstrated that although multiple domains such as sensory function and fear of falling contribute to gait performance, physical function, particularly lower limb function, accounts for a substantial proportion of the variance in gait speed⁴⁰.

However, as these muscle and neuromuscular functions are closely interrelated, evaluation of each factor independently may not fully explain its relative contribution to gait performance. Even within the domains of muscle and neuromuscular function, the relative importance and hierarchical relationships among specific components remain undetermined. Therefore, simultaneously evaluating multiple indicators may provide a more comprehensive understanding of the factors associated with gait speed. Nonetheless, relatively few studies have examined the relative contributions of multiple muscle and neuromuscular indicators within a single analytical framework, particularly the hierarchical relationships among these factors. Regression tree analysis, a decision-tree method, is a data-driven approach that identifies the relative importance of multiple factors and provides an intuitive visualization of hierarchical relationships. Unlike traditional linear models, it can reveal interaction effects and sequential decision rules, making it particularly useful for exploring the complex relationships among various muscle and neuromuscular function indicators. Therefore, we aimed to explore candidate muscle and neuromuscular function indicators associated with comfortable and maximum gait speeds in independent community-dwelling older adults and to examine their hierarchical and complementary relationships using regression tree

analysis and least absolute shrinkage and selection operator (LASSO) regression.

Materials and Methods

Study Design and Participants

This study had a cross-sectional design. The participants were community-dwelling older adults (aged ≥ 65 years) residing in Sagami-hara City, Kanagawa Prefecture, Japan. They were recruited from among the participants of geriatric syndrome checkups held in collaboration with the university and local sports facilities between 2022 and 2024. These checkups were announced via local newsletters and posters displayed at sports facilities. Older adults who (1) were aged ≥ 65 years, (2) were living independently in the community, and (3) did not have a certification of need for support or care from the long-term care insurance system in Japan, were eligible for inclusion in the study. Eligibility was confirmed at the time of recruitment. Those with (1) severe cardiovascular, pulmonary, or neurological disease; (2) implanted medical devices were excluded from the analysis. Of the 398 participants who met the inclusion criteria, 20 were excluded because they could not complete the heel-raising task as specified in the standardized measurement protocol or because valid heel-raising measurements could not be obtained. Examples included an inability to maintain stable quiet standing before movement onset and the use of a preparatory countermovement that prevented movement onset from being consistently identified from the GRF signal. Consequently, the regression tree analyses included all participants with non-missing values for the variables used in each model (376 for comfortable gait speed and 378 for maximum gait speed). For the LASSO regression analysis, an additional 63 participants were excluded because of missing values in one or more variables (SMI, $n = 1$; comfortable gait speed, $n = 2$; 5-CST, $n = 2$; unavailable GRF100 and corresponding RFD100 values, $n = 58$). Because these variables were included as candidate predictors in the LASSO regression models, a complete-case analysis was performed. Thus, 315 participants with complete data were included in the LASSO regression analysis. Given the exploratory nature of this study, the sample size was determined pragmatically to provide an adequate number of observations per candidate explanatory variable. No established method was available to determine the sample size, particularly for regression tree analysis and LASSO regression.

Health-related characteristics

The health-related characteristics of the participants were assessed with a self-administered questionnaire. Participants were asked to report physician-diagnosed medical conditions (hypertension, diabetes mellitus, cancer, chronic pulmonary disease, myocardial infarction, chronic heart failure, angina pectoris, asthma, arthritis,

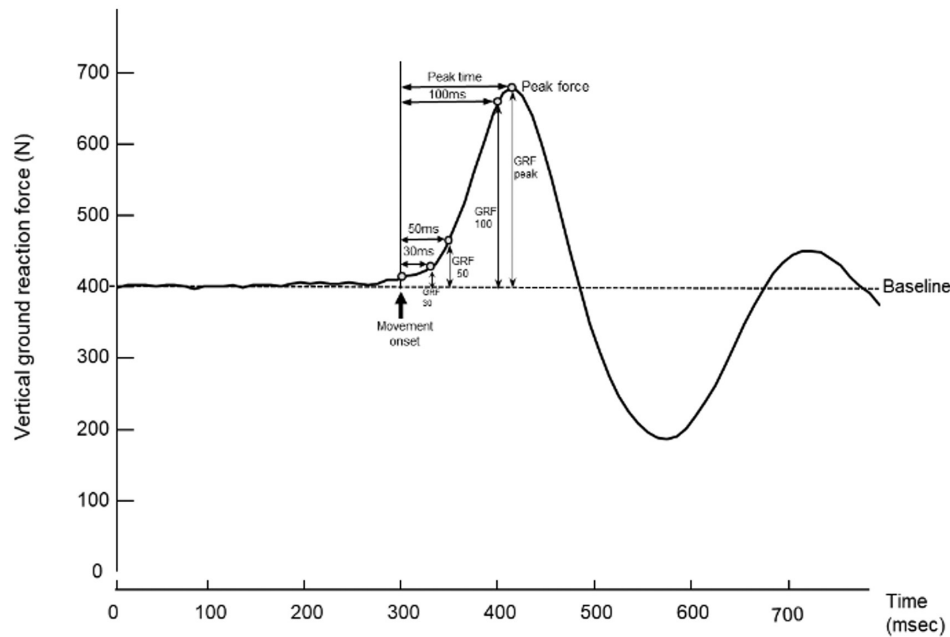


Figure 1. Example of a vertical ground reaction force (GRF) waveform during a rapid heel-raising task. Baseline GRF was defined during the quiet standing phase. Movement onset was defined as the point at which the vertical GRF exceeded the baseline by 2.5%. Peak GRF (GRFpeak) was defined as the highest increase in vertical GRF relative to the baseline during the heel-raising task, and the time from movement onset to GRFpeak was defined as the peak time. The increases in vertical GRF relative to the baseline measured at 30, 50, and 100 ms after movement onset were defined as GRF30, GRF50, and GRF100, respectively.

stroke, kidney disease, Parkinson's disease, and other conditions), current medications (number of medications), history of falls during the previous year, and painful body sites. The term "painful body sites" referred to locations where pain had persisted for at least one month. These sites included the lower back, knee, neck, shoulder, upper back, arm, leg, and other regions. The number of comorbidities and painful body sites was calculated by summing the self-reported responses. The number of medications was determined from self-reported current medication use, and polypharmacy was defined as the concurrent use of six or more medications.

Measurement of Muscle and Neuromuscular function

Appendicular skeletal muscle mass and strength (grip and knee extension) were assessed. Appendicular skeletal muscle mass (ASM) was measured using a multifrequency bioelectrical impedance analyzer (InBody 470, InBody Japan Inc). To normalize muscle mass, the skeletal muscle index (SMI) was calculated by dividing the ASM by the height squared ($ASM/height^2$). Grip strength was measured in the dominant hand using a Smedley-type dynamometer (T.K.K.5401; TAKEI Scientific Instruments Co., Ltd.). Measurements were taken in the standing position with the elbow fully extended. Knee extension

strength was measured using a handheld dynamometer (μ -Tas F-1; Anima Inc.) while participants were seated on a chair with their hips and knees flexed at 90°. The trunk was kept upright and the arms were crossed in front of the chest to minimize compensatory movement. The dynamometer was placed just above the ankle on the anterior surface of the lower leg, and the participants were instructed to push forward as hard as possible against the device. To express knee extensor strength as torque, the lower leg length was also measured. The calculated torque values were normalized to body weight and expressed as Nm/kg for statistical analyses. Grip and knee extension strength were assessed during maximum-effort isometric contractions.

The 5-CST

The participants were seated in a standard chair at a height of approximately 40 cm and maintained an upright posture with their arms crossed over their chest. They were instructed to rise to a full-standing position and return to the seated position five times consecutively as quickly as possible without using their arms for assistance. The total time taken to complete five repetitions was recorded with a stopwatch and used as the performance outcome.

Ground Reaction Force and Rate of Force Development of the Plantar Flexor Muscles During a Rapid Heel-Raising Task

1) The ground reaction force (GRF) and rate of force development (RFD) of the ankle plantar flexor muscles were assessed during a rapid heel-raising task performed on a force plate (TFG-4060, Tec Gihan Co., Ltd.), based on protocols described in previous studies^{37,38}. The sampling frequency of the force plate system was set at 100 Hz. Participants stood with both feet on a force plate, with the heels positioned 15 cm apart and the toes placed in a self-selected comfortable position. They fixated on a visual target located 90 cm in front of them. Before data collection, participants performed two or three practice trials to familiarize themselves with performing the task safely and as rapidly as possible. Participants initially maintained quiet standing for 5 s. They were instructed to initiate the heel-raising movement directly from the quiet standing position without any preparatory knee flexion or countermovement, so that movement onset could be identified consistently from the vertical GRF signal. Upon a verbal cue, participants raised their heels as quickly as possible. For safety, participants were instructed to lightly touch a stabilizing bar positioned nearby but not to support their body weight on it, to minimize its influence on the GRF measurements. Hand support was not quantified or recorded. Each participant performed three trials, with 5–10 s of rest between them. The highest of the three values was used for all subsequent analyses. All measurements were performed by trained physiotherapists following a standardized protocol.

2) The vertical component of the ground reaction force (GRF) was used in all analyses. Baseline GRF was defined as the mean value calculated over a stable 1.0-s period selected within the initial 5-s quiet standing phase prior to movement onset, during which the GRF signal remained stable. Movement onset was defined as the point at which the GRF exceeded the baseline by 2.5%. The peak GRF (GRF_{peak}) was defined as the highest increase in vertical GRF relative to the baseline during the heel-raising task, and the time from movement onset to GRF_{peak} was taken as the peak time. The GRF values at 30, 50, and 100 ms after movement onset (GRF₃₀, GRF₅₀, and GRF₁₀₀) were defined as the increases in vertical GRF from baseline measured at each corresponding time point (Figure 1). When GRF_{peak} occurred within 100 ms after movement onset, GRF₁₀₀ and RFD₁₀₀ were not calculated. The rate of force development (RFD) was calculated by dividing the increase in vertical GRF from baseline by the corresponding time interval (i.e., $RFD_{30} = GRF_{30}/30$ ms, $RFD_{50} = GRF_{50}/50$ ms, $RFD_{100} = GRF_{100}/100$ ms, and $RFD_{peak} = GRF_{peak}/\text{peak time}$)⁴¹. In addition, RFD_{max} was defined as the maximum slope of the vertical GRF-time curve. It was calculated with the built-in Maximum Slope function in LabChart 8 Reader (ADInstruments), which determines the largest increase between two successive sample

points divided by the sampling interval. Because the GRF sampling frequency was 100 Hz, the sampling interval was 0.01 s. No low-pass filtering was applied during force-plate data acquisition, and no additional smoothing or filtering was performed before calculating RFD_{max} in LabChart 8 Reader. For statistical analyses, GRF variables (GRF₃₀, GRF₅₀, GRF₁₀₀, and GRF_{peak}) were normalized to body weight by dividing the increases in vertical GRF from baseline by body weight and expressed as N/kg. RFD variables were calculated from the corresponding increases in vertical GRF from baseline before body-weight normalization and expressed as N/s.

Gait Speed

The comfortable (self-selected) and maximum gait speeds were measured using a pressure-sensitive walkway system (MW-1000; Anima Inc.). The participants walked along a 9-m walkway consisting of a 5-m measurement zone and 2-m acceleration and deceleration zones at each end. The sampling frequency of the system was set to 100 Hz. Each gait speed was measured twice, and the better of the two trials was used in the analysis.

Statistical Analysis

The values are presented as the mean $\pm$ standard deviation, median (interquartile range), or number (percentage). This study employed a multi-step analytical approach. Initially, a regression tree analysis was conducted using the Classification and Regression Tree algorithm to explore the factors most relevant to gait speed. This non-parametric approach can identify hierarchical relationships and interaction effects among the variables. The dependent variables were comfortable and maximum gait speed. The independent variables included age, sex, muscle mass, and physical function measures (grip strength, knee extension strength, 5-CST, GRF₃₀, GRF₅₀, GRF₁₀₀, GRF_{peak}, RFD₃₀, RFD₅₀, RFD₁₀₀, RFD_{peak}, and RFD_{max}). To generate the optimal tree with the highest predictive performance, tree pruning was conducted using complexity parameters (cp), taking the minimum cross-validation error as the criterion based on 10-fold cross-validation.

Due to the possibility of collinearity among the independent variables, a penalized regression analysis was performed using the LASSO model to select the appropriate variables associated with gait speed. Prior to LASSO regression, the continuous explanatory variables were standardized. The optimal penalty parameter (λ) was determined using 10-fold cross-validation, and λ_{min} , which minimizes the cross-validation error, was adopted for the final model. Additionally, a sensitivity analysis using λ_{1se} , the largest value of λ within one standard error of the minimum cross-validation error, was performed to evaluate the robustness of variable selection and model performance. Penalized regression coefficients were

reported to indicate the variables retained by the models. All statistical analyses were performed using R version 4.2.2 (R Foundation for Statistical Computing). The “glmnet” and “glmnetUtils” packages were used for the LASSO model, and the “rpart” package was used for the regression tree analysis.

Results

Characteristics of Participants

The mean age of the participants was 73.9 ± 5.3 years, and 263 (69.6%) were women. The health-related characteristics, skeletal muscle index and physical function variables are presented in Table 1. To assess potential selection bias, baseline variables (age, sex, health-related characteristics, gait speed, muscle strength, and 5-CST performance) were compared between participants included in and excluded from the regression tree and LASSO regression analyses. In the regression tree comparison, excluded participants had a significantly greater number of painful body sites than included participants ($p = 0.02$), whereas no significant differences were observed for the remaining variables (all $p > 0.05$). In the LASSO comparison, participants included in the analysis were taller ($p = 0.04$) and had greater body weight ($p = 0.03$) and skeletal muscle index ($p = 0.03$) than those excluded because of missing data. No significant differences were observed for the remaining variables (all $p > 0.05$).

Regression Tree Analysis

1) Comfortable gait speed

A regression tree analysis was performed to explore the candidate indicators associated with comfortable gait speed (Figure 2). The final pruned tree, selected using 10-fold cross-validation, had a complexity parameter of 0.041, a cross-validation error of 0.970, three terminal nodes, and a maximum depth of two. The initial split was based on the 5-CST, followed by a second split on the RFDmax among participants with a prolonged 5-CST. Participants with a 5-CST ≥ 6.3 s and RFDmax < 3631.8 N/s were classified into terminal node 3, with the lowest mean comfortable gait speed (131.3 ± 17.0 cm/s), whereas those with a 5-CST < 6.3 s were classified into terminal node 5 (150.7 ± 18.9 cm/s), which had the highest mean comfortable gait speed.

2) Maximum gait speed

A regression tree analysis was performed to explore the candidate indicators associated with maximum gait speed (Figure 3). The final pruned tree, selected using 10-fold cross-validation, had a complexity parameter of 0.021, a cross-validation error of 0.859, six terminal nodes, and a maximum depth of four. The tree selected 5-CST, RFDmax, and grip strength as the splitting

Table 1. Characteristics of participants and outcome measures.

Variables	Value
Age (years)	73.9 ± 5.3
Women, n (%)	263 (69.6)
Height (cm)	156.8 ± 8.1
Body weight (kg)	54.7 ± 9.2
Body mass index (kg/m ²)	22.2 ± 3.0
Skeletal muscle index (kg/m ²)	6.4 ± 0.9
Number of comorbidities	1 (0–3)
Number of medications	1 (0–3)
Polypharmacy (≥ 6 medications), n (%)	17(4.6)
Number of painful body sites	1 (0–1)
History of falls, n (%)	60(15.9)
Physical function variables	Value
Comfortable gait speed (cm/s)	145.8 ± 20.1
Maximum gait speed (cm/s)	192.4 ± 28.2
Grip strength (kg)	26.7 ± 6.7
Knee extension strength (Nm/kg)	1.4 ± 0.5
Five-times chair stand test (s)	5.9 ± 1.4
GRF30 (N/kg)	0.9 ± 0.5
GRF50 (N/kg)	1.6 ± 1.0
GRF100 (N/kg)	3.2 ± 1.6
GRFpeak (N/kg)	4.7 ± 1.1
RFD30 (N/s)	1627.9 ± 994.3
RFD50 (N/s)	1663.7 ± 1109.8
RFD100 (N/s)	1740.6 ± 929.8
RFDpeak (N/s)	2095.0 ± 852.8
RFDmax (N/s)	3761.3 ± 1263.0

N = 378. Values are presented as mean $\pm$ standard deviation (SD), median (interquartile range), or number (%). Missing data were present for skeletal muscle index (n = 1), comfortable gait speed (n = 2), five-times chair stand test (n = 2), GRF100 (n = 58), RFD100 (n = 58), number of medications (n = 5), and history of falls (n = 1). Percentages were calculated using the number of participants with available data for each variable. GRF, ground reaction force; RFD, rate of force development; GRF30, GRF50, and GRF100: increases in vertical GRF from baseline at 30, 50, and 100 ms after movement onset, respectively; GRFpeak: highest increase in vertical GRF from baseline during the heel-raising task; RFD30, RFD50, and RFD100: RFD calculated by dividing the corresponding increase in vertical GRF from baseline by the corresponding time interval; RFDpeak: GRFpeak divided by peak time; RFDmax: maximum slope between successive points on the vertical GRF–time curve.

variables. Participants with a 5-CST ≥ 6.7 s and RFDmax < 3460.0 N/s were classified into terminal node 4, which had the lowest mean maximum gait speed (165.8 ± 19.6 cm/s), whereas those with a 5-CST < 4.5 s were classified into terminal node 11, which had the highest mean

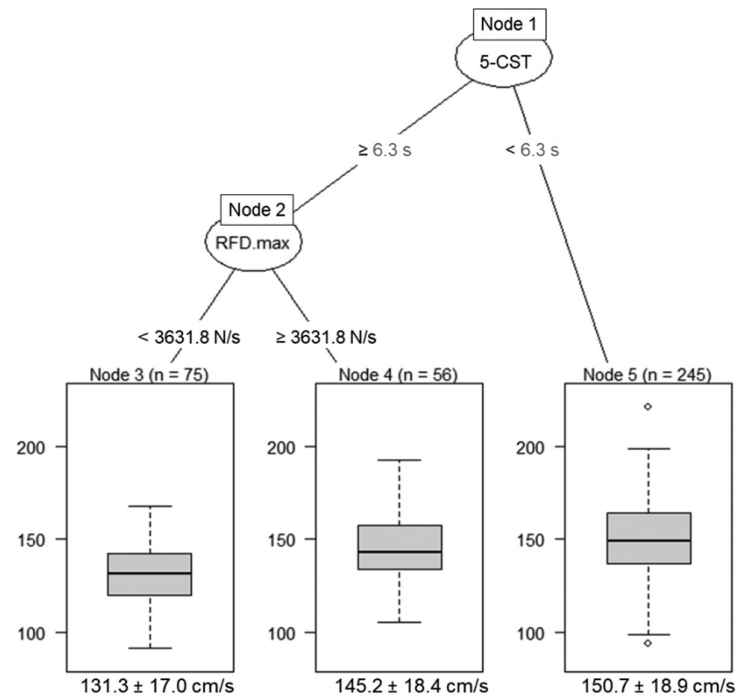


Figure 2. Regression tree for comfortable gait speed. The regression tree was pruned using complexity parameter selected via 10-fold cross-validation. The final tree had a complexity parameter of 0.041, a cross-validation error of 0.970, three terminal nodes, and a maximum depth of two. Participants were classified into three terminal nodes based on split thresholds of the 5-CST and RFDmax. Each terminal node displays the sample size and mean $\pm$ standard deviation for comfortable gait speed and includes a box-and-whisker plot representing the distribution of gait speed within the node.

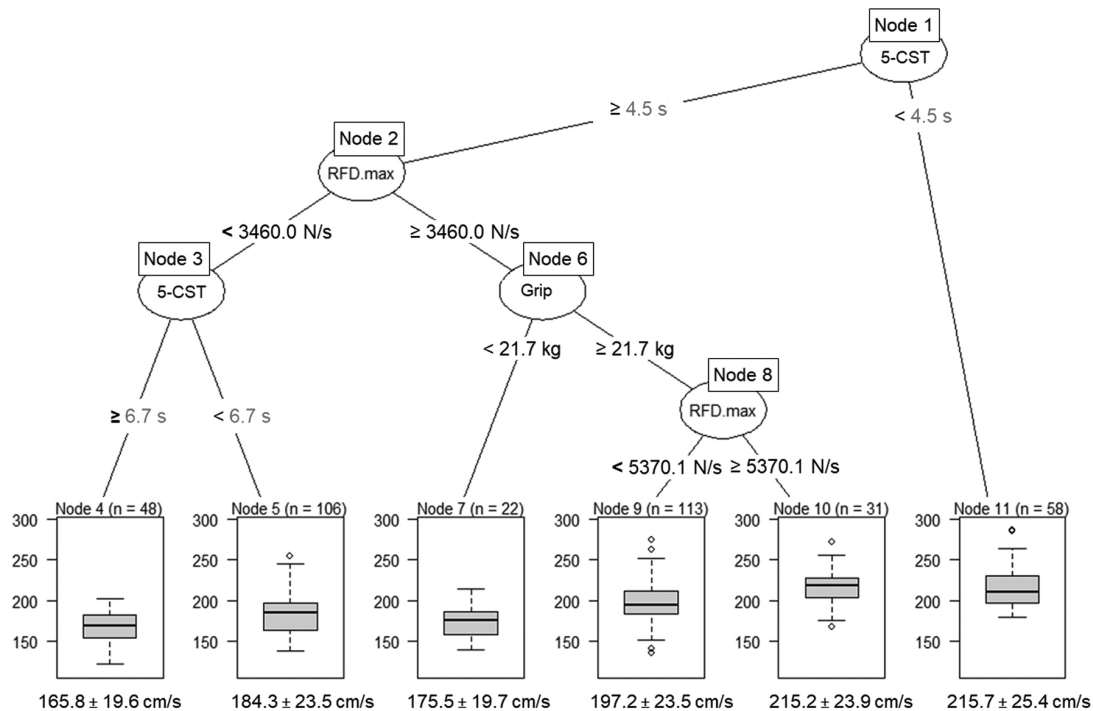


Figure 3. Regression tree for maximum gait speed. The regression tree was pruned using complexity parameters selected via 10-fold cross-validation. The final tree had a complexity parameter of 0.021, a cross-validation error of 0.859, six terminal nodes, and a maximum depth of four. Participants were classified into six terminal nodes based on split thresholds of the 5-CST, RFDmax, and grip strength. Each terminal node displays the sample size and mean $\pm$ standard deviation for maximum gait speed and includes a box-and-whisker plot representing the distribution of gait speed within the node.

Table 2. LASSO regression analysis for comfortable and maximum gait speed.

	Comfortable gait speed		Maximum gait speed	
	Penalized coefficients $\lambda_{\min}$ model (n = 6 variables)	Penalized coefficients λ_{1se} model (n = 2 variables)	Penalized coefficients $\lambda_{\min}$ model (n = 9 variables)	Penalized coefficients λ_{1se} model (n = 7 variables)
Age (years)	-0.036		-0.78	-0.25
Sex (women)				
Skeletal muscle index(kg/m ²)			3.02	
Grip strength (kg)			0.49	0.30
Knee extension strength (Nm/kg)	40.75		57.63	10.08
Five-times chair stand test (s)	-3.34	-1.75	-6.12	-4.60
GRF30 (N/kg)				
GRF50 (N/kg)			1.60	
GRF100 (N/kg)	0.34			
GRFpeak (N/kg)	3.82	2.23	4.32	1.02
RFD30 (N/s)				
RFD50 (N/s)				
RFD100 (N/s)				
RFDpeak (N/s)			0.000146	0.00199
RFDmax (N/s)	0.000264		0.00092	0.00228
Model performance parameters	$\lambda=0.955$	$\lambda=4.231$	$\lambda=0.386$	$\lambda=3.953$
	RMSE=18.21	RMSE=18.87	RMSE=23.70	RMSE=24.62
	Cross-validated $R^2=0.18$	Cross-validated $R^2=0.12$	Cross-validated $R^2=0.30$	Cross-validated $R^2=0.25$

The sample size was 315. The coefficients represent penalized estimates from the LASSO regression model. The variables for which the coefficients were calculated were selected using the LASSO models. $\lambda_{\min}$ and λ_{1se} were selected using 10-fold cross-validation. Then, the root mean squared error (RMSE) and cross-validated R^2 were then calculated from out-of-fold predictions. Sex was included as a categorical variable, with "men" was used as the reference category. Although continuous predictors were standardized for model fitting, coefficients are presented on the original predictor scale as returned by the glmnet coefficient output. GRF, ground reaction force; RFD, rate of force development; RFD30, RFD50, and RFD100: RFD calculated by dividing the corresponding increase in vertical GRF from baseline by the corresponding time interval; RFDpeak: GRFpeak divided by peak time; RFDmax: maximum slope between successive points on the vertical GRF–time curve.

maximum gait speed (215.7 ± 25.4 cm/s). The remaining terminal nodes showed intermediate mean maximum gait speeds for combinations of RFDmax and grip strength.

LASSO Regression Analysis

1) Comfortable gait speed

LASSO regression was performed using 10-fold cross-validation to reduce overfitting and address potential multicollinearity among the candidate predictors. In the $\lambda_{\min}$ model ($\lambda = 0.955$), age, knee extension strength, 5-CST, GRF100, GRFpeak, and RFDmax were selected. The λ_{1se} model ($\lambda = 4.231$) retained 5-CST and GRFpeak. The $\lambda_{\min}$ model showed a root mean squared error (RMSE) of 18.21 cm/s and a cross-validated R^2 of 0.18, whereas the λ_{1se} model had an RMSE of 18.87 cm/s and a cross-validated R^2 of 0.12 (Table 2).

2) Maximum gait speed

For maximum gait speed, the $\lambda_{\min}$ model ($\lambda = 0.386$) selected age, SMI, grip strength, knee extension strength, 5-CST, GRF50, GRFpeak, RFDpeak, and RFDmax. The λ_{1se} model ($\lambda = 3.953$) retained age, grip strength, knee extension strength, 5-CST, GRFpeak, RFDpeak, and RFDmax. The $\lambda_{\min}$ model showed an RMSE of 23.70 cm/s and a cross-validated R^2 of 0.30, whereas the λ_{1se} model showed an RMSE of 24.62 cm/s and a cross-validated R^2 of 0.25 (Table 2).

Discussion

In this exploratory study, we investigated candidate muscle and neuromuscular function indicators associated with comfortable and maximum gait speed in community-

dwelling older adults using regression tree and LASSO regression analyses. The novelty of this study lies in the comprehensive evaluation of multiple muscle-related indicators (12 candidate indicators) with complementary exploratory analytical approaches (regression tree and LASSO regression) rather than focusing on a limited number of conventional muscle strength measures. The main findings were that lower-limb functional performance, represented by the 5-CST, and rapid force-generating capacity, represented by RFDmax, were consistently selected across both analytical approaches as candidate indicators associated with gait speed. Grip strength emerged as an additional factor associated with maximum gait speed in both analyses. In addition, the LASSO model selected several other strength- and force-related variables, including knee extension strength, and GRF-related measures for maximum gait speed. These findings suggest that gait performance in independent older adults may be associated with integrated functional performance and rapid force-generating capacity, while broader strength-related factors may provide complementary explanatory information.

The 5-CST was consistently selected across both analytical approaches, suggesting that chair-stand performance may represent a fundamental component of functional capacity associated with gait ability. Unlike isolated measures of maximal muscle strength, the 5-CST reflects functional lower-limb performance involving coordinated multijoint movement, dynamic postural control, and repeated body weight transfer, while also placing substantial demand on the proximal lower-limb extensor function.

This interpretation is consistent with previous studies demonstrating that sit-to-stand power is more strongly associated with gait speed than isolated knee extension strength, further supporting the potential importance of functional lower limb power in mobility performance^{33,34,42}.

From a biomechanical perspective, these findings may also reflect age-related alterations in joint kinetics during walking. Previous studies have demonstrated reductions in ankle joint power in older adults accompanied by compensatory increases in the proximal joint contribution, a phenomenon described as a distal-to-proximal shift^{27,43}. In this context, the 5-CST may reflect the functional consequences of these biomechanical adaptations, as chair-rise performance places greater demand on the proximal lower limb extensors, particularly the hip and knee extensors, which may compensate for a reduced distal ankle contribution⁴⁴.

RFDmax was also consistently selected following the 5-CST in both gait conditions, highlighting the potential importance of rapid force-generating capacity in gait performance. This finding aligns with previous evidence demonstrating associations between lower-extremity rapid force-generating capacity and maximum walking speed, mobility performance, and speed-dependent functional tasks in older adults³⁷⁻³⁹. Aging is associated

with preferential atrophy of type II muscle fibers and reduced neuromuscular activation efficiency¹⁰, both of which impair the rate of force generation^{16,17,27,45,46}. Consequently, rapid force-generating capacity may decline even when maximal muscle strength is relatively preserved. Given the important contribution of ankle plantar flexor function to gait propulsion, particularly at faster gait speeds^{27,45,46}, these findings suggest that rapid plantar flexor force generation may be associated with gait performance, especially under conditions requiring higher walking speeds.

Although the LASSO model selected multiple GRF- and RFD-related variables, the regression tree analysis selected only RFDmax within the hierarchical model. This discrepancy may reflect methodological differences between the two analytical approaches. While LASSO may retain multiple correlated predictors under multicollinearity, regression tree analysis selects the single variable with the greatest discriminatory value at each split. Several force-related parameters were retained in the exploratory analyses, among these correlated variables, RFDmax was consistently selected across both analytical approaches and may represent a candidate indicator of rapid force-generating capacity.

Knee extension strength was selected only in the LASSO model and was not retained in the regression tree analysis. This finding suggests that knee extensor strength may provide additional information beyond the variables retained in the regression tree model, whereas the 5-CST and RFDmax were more consistently selected across analytical approaches. One possible explanation is that knee extension strength may reflect functional aspects that partially overlap with composite measures such as the 5-CST, thereby contributing to the LASSO model, although less strongly than the 5-CST or RFDmax. In addition, because the relationship between maximal muscle strength and mobility performance may be nonlinear³¹, the predominance of relatively high-functioning participants may have contributed to the lower prominence of maximal knee extensor strength in the exploratory models.

Grip strength was associated only with maximum gait speed, suggesting that the factors associated with comfortable and maximum gait speed differed. Comfortable walking reflects habitual locomotion with a relatively low physiological demand, whereas maximum walking represents the upper limit of locomotor capacity. The selective association between grip strength and maximum gait speed may indicate that performance under high-demand walking conditions reflects a broader physical capacity beyond localized lower limb function. This interpretation is consistent with previous studies showing that grip strength is associated with lower-extremity strength, walking performance, and general health outcomes in older adults^{47,48}.

The skeletal muscle index was selected only in the LASSO model, suggesting that muscle mass may provide supplementary explanatory information in

addition to functional and neuromuscular variables. This interpretation aligns with previous evidence indicating that muscle strength and power are more strongly associated with physical function than is muscle mass alone⁴⁹.

The sensitivity analysis using the λ_{1se} criterion showed different patterns between comfortable and maximum gait speed. For comfortable gait speed, the number of selected variables decreased from six at λ_{min} to two at λ_{1se} , with a modest reduction in cross-validated performance. This finding indicates that variable selection was sensitive to the degree of penalization; accordingly, the variables selected only at λ_{min} may be more sensitive to the degree of penalization and should therefore be interpreted cautiously. Comfortable gait speed may also be related to by physical, cognitive, and environmental factors not included in the present analysis. In contrast, for maximum gait speed, seven of the nine variables selected at λ_{min} were retained at λ_{1se} , with only modest changes in RMSE and cross-validated R^2 . This result suggests that the variables identified for maximum gait speed were relatively more robust to the choice of penalty parameter and that multiple muscle-function variables may be associated with it. Nevertheless, because bootstrap resampling or repeated cross-validation was not performed, further studies are warranted to confirm the stability of these findings.

These findings also underscore the potential importance of evaluating qualitative aspects of neuromuscular function, in addition to maximal muscle strength, when investigating gait performance in relatively high-functioning community-dwelling older adults.

However, several limitations should be considered when interpreting these findings. First, the study population consisted predominantly of relatively high-functioning community-dwelling older adults, which may limit the generalizability to frail populations. Furthermore, participants were volunteers who attended community health checkups, and therefore may not represent the broader population of community-dwelling older adults. Second, the cross-sectional design precludes inferences regarding temporality and causality. External validation with independent samples would also be required to confirm the generalizability of these findings. Third, selection bias cannot be entirely excluded. Participants excluded from the regression tree analyses had a greater number of painful body sites. In addition, the LASSO regression analysis was based on complete-case data, and participants included in the LASSO analysis were slightly taller and had greater body weight and skeletal muscle index than those excluded because of missing data. Therefore, the possibility of selection bias related to missing data should be considered when interpreting the findings of the LASSO analysis. Fourth, because RFDmax was calculated from unfiltered GRF data as the maximum slope between successive sample points, it may have been sensitive to high-frequency noise. In addition, although participants

were instructed to use the stabilizing bar only for safety without supporting body weight, the actual loading applied to the bar was not quantified; therefore, its potential influence on the GRF measurements cannot be completely excluded. Furthermore, the test-retest reliability of the heel-raising measurement protocol was not evaluated in the present study. Accordingly, caution is required when interpreting RFDmax, and future studies should evaluate the reliability and validity of this measurement protocol with standardized signal-processing methods. Fifth, regression tree models were intentionally pruned to reduce overfitting; however, cross-validation errors indicated only modest predictive performance. Therefore, the regression tree findings should be interpreted as exploratory rather than as definitive predictive models. In addition, variable-selection stability in the LASSO regression analysis was assessed by comparing the λ_{min} and λ_{1se} criteria rather than by bootstrap resampling or repeated cross-validation. The marked reduction in selected variables for comfortable gait speed indicates sensitivity to the penalty criterion, highlighting the need for external validation. Finally, physical activity level, cognitive function, sensory impairment, fear of falling, and other potentially relevant factors were not evaluated. Therefore, residual confounding cannot be excluded.

In conclusion, among relatively high-functioning community-dwelling older adults, gait speed appears to be associated not only with muscle strength but also with neuromuscular function, particularly the capacity to generate force rapidly. These findings highlight the potential importance of assessing qualitative aspects of neuromuscular function when evaluating mobility in this population.

Ethics Approval

The study protocol was approved by the institutional review board of the School of Allied Health Sciences at Kitasato University (approval number: 2018-008B-2) and complied with the principles of the Declaration of Helsinki.

Consent to Participate

All participants provided written informed consent for the exclusive use of their data for scientific research after receiving a detailed explanation of the purpose of the study. The participants were informed that they could withdraw from the study at any time without penalty.

Authors' Contributions

Miki Sakamoto contributed to the study conception and design, data collection, analysis and interpretation of data, and preparation of the manuscript. Naoto Kamide contributed to the study conception and design, acquisition of subjects, data collection and analysis, and writing-review and editing of the manuscript. Masataka Ando contributed to acquisition of subjects and data, and data analysis. Hitoshi Sugawara and Chigaya Tadano contributed to methodology, data analysis, and writing-review and editing. All authors read and approved the final manuscript. Miki Sakamoto accepts responsibility for the integrity of the data analysis.

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