

Motor Parameters Derived from Three-Dimensional Motion-Analysis in Chinese Adults: A Nationwide Cross-Sectional Study

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Abstract

Background: Studies providing reference ranges for motor parameters are scarce. We aimed to establish reference ranges for motor parameters in adults in China using a three-dimensional (3D) motion-analysis system.

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Materials and methods: In this study, adults without self-reported mobility limitations were recruited from 13 hospitals across China between 2021 and 2023. Participants completed a series of actions on a three-meter walkway adhering to uniform instructions and procedures. A medical-grade 3D motion-analysis system evaluated motor function. Multivariable Bayesian linear regression models were used to derive 95% credible intervals.

Results: We enrolled 1,796 participants (58.98 ± 14.91 years, 46.66% males). All motor parameters were stable throughout 20 to 50 years and changed thereafter. Older age was associated with decreased stride length and stride speed, and increased timed up-and-go test time, whereas step width remained stable. Male participants showed greater step height and step width than female participants. The Bland–Altman analysis revealed good agreement between the two test occasions for all parameters. We established reference ranges for 54 motor parameters representing upper-limb function, gait features, and postural stability. An interactive web-based application (testcog2b.ruiyicas.com:8099) was created to provide detailed reference ranges.

Discussion: These reference ranges fill a critical gap in normative motor data for the Chinese population, as previous studies were limited by small samples and inconsistent methodologies. The accompanying web-based application further enhances accessibility, allowing clinicians to interpret patient performance across different motor domains more easily.

Conclusion: This study provides reference ranges for various motor parameters, which can serve as a benchmark for future clinical applications.

Keywords: motor function, reference range, three-dimensional motion-analysis system

Introduction

Gait, which is affected primarily by the musculoskeletal, nervous, and cardiovascular systems, is a critical indicator of health status in older adults. Motor disorders not only diminish quality of life but also correlate with an elevated risk of falls, death^[1–3], and dementia^[4–6], and therefore demand serious attention.

Clinically, motor assessment relies on rating scales, questionnaires, and tests conducted by medical personnel. More recently, quantitative assessments using diverse types of sensors and ubiquitous computing have provided more objective and precise kinematic data, allowing for the early detection of motor disorders and longitudinal comparisons. These methods can capture the intricacies of bodily movements, provide multi-dimensional clinical insights, and consequently yield a large number of parameters. Although studies on quantitative assessments and related parameters are increasing markedly, research on reference ranges and cut-off points for various motor parameters is scarce. Walking speed, the most widely studied quantitative motor parameter, is defined as slow if usual walking speed is $< 1 \text{ m/s}$ ^[7,8] or $\leq 0.8 \text{ m/s}$ ^[7,9,10], depending on the criterion used. However, reference ranges for other important motor parameters, such as step height, step

width, posture control, and upper-limb motor function, are lacking.

Therefore, this study aimed to establish reference ranges for 54 motor parameters in healthy adults from communities across China. This study used a medical-grade three-dimensional (3D) motion-analysis system that integrates a high-resolution red, green, and blue (RGB) camera, a time-of-flight (ToF) sensor, and computer vision algorithms for motor feature extraction. To assess the performance of the system, we evaluated the test-retest reliability and agreement.

Materials and methods

Study setting and participants

This nationwide, multicenter study was conducted between September 2021 and March 2023. To enhance the generalizability of the study sample, participants were recruited from 13 hospitals across Northeast, East, North, Central, South, and Southwest China. Inclusion criteria were voluntarily signed informed consent, age ≥ 18 years, and normal motor function with no self-reported gait disturbance. Exclusion criteria were central nervous system disease, severe physical disease, bone and joint disease, inability to complete the gait test, or a Mini-Mental State Examination score < 26 .

Participants were recruited as community-dwelling volunteers through online advertisements rather than as hospital patients. The participating hospitals served as standardized assessment and recruitment sites, providing trained personnel and facilities for clinical screening. The primary recruitment criteria were normal cognitive and motor functions, as well as absence of diseases listed in the exclusion criteria. To ensure the accuracy of health status assessment, a two-step screening process was implemented. First, participants completed a self-reported health assessment based on the predefined inclusion and exclusion criteria. Second, individuals who passed the initial screening underwent a general consultation and physical examination conducted by trained members of the medical team. Participants were considered eligible only when no clinically apparent neurological, musculoskeletal, or other medical condition that could affect motor function was identified. In addition, participants were required to have normal motor function, no self-reported gait disturbance, and the ability to independently complete the standardized motor assessment protocol. This study was approved by the Ethics Committee of Peking Union Medical College Hospital (HS-3076, July 27, 2021). All participants signed an informed consent form.

To ensure the generalizability of the study sample, participants were stratified into 20 groups based on age (18–49, 50–59, 60–69, 70–79, and > 80 years), sex (male and female), and education level (junior high school and below and high school and above). To establish a reliable

reference range, the Clinical and Laboratory Standards Institute^[11] recommends 120 reference individuals per subgroup, although as few as 20 samples may be acceptable. Considering the relatively small population sizes in the 18–49-year age group with junior high school education or below and in the ≥ 80 -year age group, at least 20 participants were to be included in these 6 subgroups, while 120 participants were to be included in each of the remaining 14 subgroups. Therefore, the required sample size for this study was $120 \times 14 + 20 \times 6 = 1800$ participants. Considering a non-response rate of 5%, the final target sample size was 1890 participants.

Measurements

Instruments

Motor function was evaluated using the ReadyGo Motion Analysis System registered with the National Medical Products Administration (NMPA) of China. This device used an Azure Kinect, a 3D camera with a 30-Hz sampling frequency developed by Microsoft Corporation, as the motion sensor. As illustrated in Figure 1, the Kinect camera utilizes both two-dimensional (2D) optical RGB images and ToF depth video frames to generate the 3D human skeleton structure based on the point cloud of the human body. This allowed us to obtain more precise joint point coordinates and compute body position in space from a single front view, thereby calculating motor parameters throughout the entire gait process. Support vector machine and bidirectional

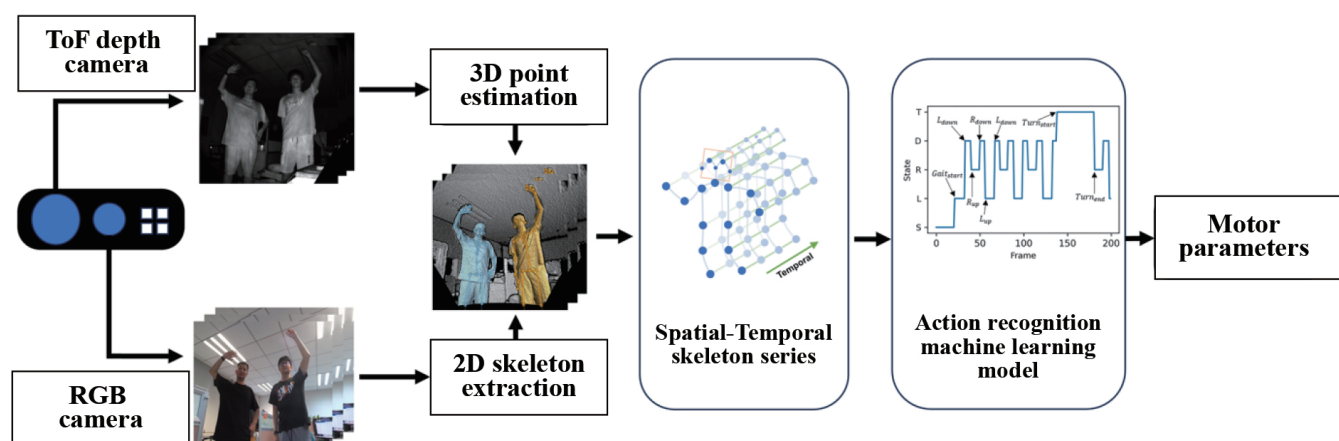


Figure 1: Illustration of motor parameters extraction.

long short-term memory classifiers were used to train the spatiotemporal features to identify gait types in each walking frame. Subsequently, the frame labels facilitated the derivation of the gait semantics and the calculation of the relevant motor parameters. To ensure optimal model generalization performance, a 10-fold cross-validation strategy was adopted during classifier training. The embedded gait analysis algorithms were validated in Jing et al.^[12], which showed an average error rate of 3.17% for gait parameters, the state-of-the-art performance in this domain. According to the NMPA-approved device instruction manual, the absolute errors of gait parameters were less than 4%, which supports the results presented in a previous study^[12].

Data storage, transmission, and quality control

Gait videos were regularly stored on hard drives. Videos from different sites were transferred offline via hard drives or through encrypted compressed files transmitted over networks or email. Operators were trained to handle data collection and ensure the accuracy of recordings. Quality control measures included regular monitoring and validation of data integrity. Weekly back-end data checks were conducted to monitor enrollment status and ensure data quality across sites. When gait parameter outliers were identified, researchers at the respective sites were contacted to investigate and collect new videos as necessary.

Motor actions and data processing

Each participant completed a series of actions on a 3-m walkway in front of the Azure Kinect depth camera, adhering to uniform instructions and procedures. These actions encompass those found in the Scale for the Assessment and Rating of Ataxia (SARA)^[13], the Unified Parkinson's Disease Rating Scale (UPDRS)^[14], the Tinetti scale^[15], and the Short Physical Performance Battery^[16]. A detailed list of the movements and recorded items is provided in Supplementary Table 1.

The software extracted 54 motor parameters from the aforementioned actions. These included 11 parameters representing completion time and degree of sway, the latter being defined as the maximum angle between the torso (the vector connecting the center of the pelvis

Table 1: Baseline characteristics of the study population.

Variables	<i>N</i> = 1796
Age (years)	58.98 ± 14.91
Age group	
18–49	424 (23.61%)
50–59	442 (24.61%)
60–69	480 (26.73%)
70–79	303 (16.87%)
> 80	147 (8.18%)
Sex	
Male	838 (46.66%)
Female	958 (53.34%)
Education level	
Junior high school and below	1031 (57.41%)
High school and above	765 (42.59%)
Dominant hand	
Right	1783 (99.28%)
Left	13 (0.72%)
Height (cm)	163.52 ± 7.89
Body weight (kg)	64.48 ± 11.62
BMI (kg/m ²)	24.04 ± 3.51

to the neck) and the normal vector of the ground. We extracted 21 motor parameters from the 3-m walking test, including gait speed; step height; step width; cadence; stride length; cycle duration variability, swing time asymmetry, and swing, stance, and double-support phases. The definitions and schematic diagrams can be found in Figure 2. The data processing step operates automatically within the instrument's model, which labels data sequences for gait parameter extraction. There are approximately 15 to 21 gait cycles per individual for data extraction. Gait cycles during turnaround intervals were discarded to ensure accuracy, with only data from straight walking intervals being utilized. Initial and final gait segments were also excluded due to gait instability at these points. The average value of each parameter was calculated to provide the final gait parameter results. For distance-related parameters, the minimal reliable difference is 0.01 m. For time-related parameters, the minimal reliable difference is 0.01 s. Step height in our calculations was derived using the ankle position.

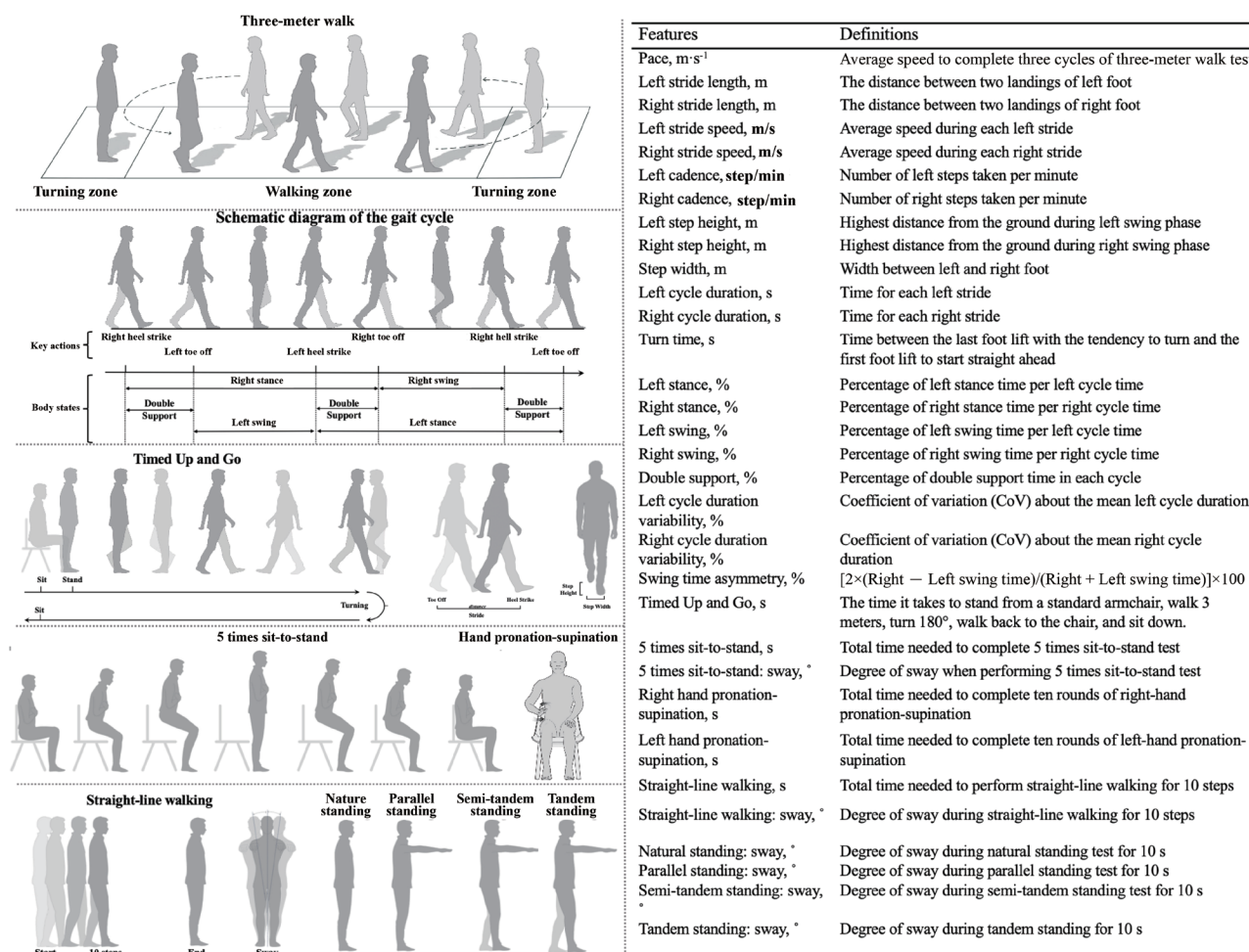


Figure 2: The schematic diagrams and definitions of motor parameters.

Step height was derived using the ankle position. Specifically, we used the ankle position in a static state as the reference point. The step height was then calculated as the difference between this reference position and the highest point of the ankle during the gait cycle.

Specifically, we used the ankle position in a static state as the reference point. The step height was then calculated as the difference between this reference position and the highest point of the ankle during the gait cycle. The average values were recorded for each parameter.

Test-retest performance evaluation of the motor parameters

To evaluate the test-retest performance of the motor parameters, we randomly selected 10% of the participants to undergo the movements test three months after the initial test. For a comprehensive evaluation of test-retest performance, we assessed both agreement and reliability^[17]. Agreement assessed the closeness of the values measured between the two tests. Bland–

Altman analysis is a typical method for evaluating the degree of agreement, which uses the average differences between two tests (bias) and the expected range that includes 95% of the future differences between two tests (limits of agreement). Reliability is the ability to distinguish between participants despite measurement errors in assessing the correlation between two tests of the target population. The intraclass correlation (ICC) is a typical index of reliability that is generally defined as the variance between participants/(variance between participants + measurement error). Agreement is a parameter that differentiates within-participant variation over time by two different raters, whereas reliability is used to differentiate between-participant variation. We chose the ICC based on a two-way mixed-effects model,

mean rating ($k = 2$), and absolute agreement. Statistical analyses were performed using SAS 9.4 software (SAS Institute Inc., Cary, NC, USA) with all statistical tests being two-tailed and the significance level set at a P -value of < 0.05 .

Establishment of reference ranges

Multivariate Bayesian linear regression (BLR) models were used to derive 95% credible intervals (95% CIs) for all motor parameters, including age, sex, and education level, as independent variables. Accounting for possible non-linear relationships between age and motor performance, we modeled age as a 3-knot restricted cubic spline. Supplementary material 1 provides details on model establishment and prior specifications. The posterior regression coefficients were sampled using four chains, each with 8000 iterations. Using these posterior distributions, we computed the proportion of distributions that exceeded 0. This allowed us to estimate the probability that age, sex, and education level were associated with functional outcomes. We used all observation points from the four chains to perform subtraction and calculated the average and 95% CI of the difference while altering the independent variables. The independent variables age, sex, and education were represented as “50 years vs. 70 years old,” “female vs. male,” and “low education vs. high education,” respectively. The percentage of differences exceeding 0 was documented. A probability > 0.7 or < 0.3 was considered relevant between the motor parameter and independent variables. Based on the posterior distribution, the 95% confidence intervals corresponding to each age group were calculated and stratified according to sex and education. Reference ranges were established using the 95% CIs generated above with 2.5% of the observed values falling above and 2.5% falling below the interval bounds. All the BLR models were constructed using the “PyMC” package in Python 3.11 (Python Software Foundation, Wilmington, DE, USA).

Role of the funding source

The funding sources had no role in study design; in the collection, analysis, and interpretation of data; in the writing of the report; or in the decision to submit the paper for publication. The corresponding

author and first authors had full access to all the data in the study and accept responsibility to submit for publication.

Equity, diversity, and inclusion (EDI) statement

We are committed to promoting equity, diversity, and inclusion in our organization. We value the unique perspectives and backgrounds of all individuals and strive to create an environment where everyone feels respected and empowered. We believe that fostering a diverse and inclusive culture enhances our ability to innovate and better serve our community. We are dedicated to ensuring equal opportunities for all and actively working to eliminate barriers.

Results

We enrolled 1796 participants from 13 hospitals. The average age was 58.98 years (standard deviation [SD] = 14.91) and males accounted for 46.66%. Their mean height and body weight were 163.52 cm (SD = 7.89) and 64.48 kg (SD = 11.62), respectively. A total of 765 (42.59%) participants had completed high school or higher education. Table 1 shows the basic information of the participants.

Associations of age, sex, and education level with motor parameters

Descriptive summary statistics of the motor parameters across the age groups are shown in Table 2. Most parameters were significantly associated with age, with the exception of asymmetry. These findings suggest that, with increasing age, the time required to complete all tests increased, coupled with an increasing degree of sway. Additionally, older age was associated with a decrease in gait speed, stride length, stride speed, cadence, and swing phase, accompanied by an increase in step width, stride time, turn time, stance phase, and double-support phase. The relationships between these parameters, sex, and education level are shown in Table 3. We found no between-sex differences in the time to complete the hand pronation–supination test or the degree of sway in parallel, semi-tandem, and tandem standings. Although male participants completed the 5-times sit-to-stand test faster than female participants, the degree of sway

Table 2: Motor parameters, overall and stratified by age.

Motor parameters	Overall	18–49 years	50–59 years	60–69 years	70–79 years	> 80 years	<i>p</i>
Right hand pronation-supination, s	8.83 ± 2.47	8.35 ± 2.22	8.50 ± 1.86	8.98 ± 2.37	9.22 ± 2.86	9.86 ± 3.61	< 0.001
Left hand pronation-supination, s	9.36 ± 2.69	8.76 ± 2.60	9.10 ± 2.16	9.59 ± 2.83	9.78 ± 2.87	10.05 ± 3.14	< 0.001
5 times sit-to-stand, s	12.76 ± 3.22	11.95 ± 2.55	12.33 ± 2.49	12.69 ± 2.87	13.12 ± 3.00	15.67 ± 5.81	< 0.001
5 times sit-to-stand: sway, %	29.82 ± 6.96	27.5 ± 5.95	29.45 ± 6.32	30.22 ± 6.68	31.63 ± 7.64	32.79 ± 8.82	< 0.001
Natural standing: sway, %	11.64 ± 5.93	11.16 ± 5.6	11.44 ± 5.74	11.93 ± 6.18	12.04 ± 5.88	12.67 ± 6.80	0.010
Parallel standing: sway, %	11.53 ± 5.7	10.52 ± 5.76	11.6 ± 5.75	11.66 ± 4.87	12.39 ± 6.24	12.47 ± 6.67	< 0.001
Semi-tandem standing: sway, %	12.13 ± 5.76	10.83 ± 5.98	12.15 ± 5.13	12.60 ± 5.55	12.93 ± 6.43	12.64 ± 6.10	< 0.001
Tandem standing: sway, %	13.63 ± 5.79	11.74 ± 5.67	13.64 ± 5.58	14.28 ± 5.64	14.59 ± 5.71	15.02 ± 6.28	< 0.001
Straight-line walking, s	12.29 ± 3.72	11.42 ± 3.02	11.95 ± 3.23	12.13 ± 3.02	13.29 ± 4.02	14.68 ± 6.17	< 0.001
Straight-line walking: sway, %	21.04 ± 8.04	18.75 ± 7.01	21.06 ± 7.73	21.53 ± 8.42	22.14 ± 7.81	24.14 ± 8.84	< 0.001
Timed up and Go, s	12.33 ± 3.09	10.90 ± 2.11	11.80 ± 2.18	12.22 ± 2.56	13.36 ± 2.74	16.62 ± 5.12	< 0.001
Gait speed, m/s	1.18 ± 0.26	1.31 ± 0.21	1.23 ± 0.21	1.15 ± 0.23	1.04 ± 0.22	0.90 ± 0.27	< 0.001
Left stride length, m	1.12 ± 0.19	1.19 ± 0.18	1.15 ± 0.17	1.12 ± 0.16	1.05 ± 0.16	0.90 ± 0.18	< 0.001
Right stride length, m	1.11 ± 0.17	1.17 ± 0.16	1.14 ± 0.14	1.12 ± 0.16	1.04 ± 0.15	0.89 ± 0.18	< 0.001
Left stride speed, m/s	1.25 ± 0.27	1.39 ± 0.24	1.30 ± 0.24	1.23 ± 0.23	1.11 ± 0.22	0.98 ± 0.25	< 0.001
Right stride speed, m/s	1.25 ± 0.26	1.39 ± 0.22	1.30 ± 0.22	1.24 ± 0.22	1.11 ± 0.22	0.97 ± 0.26	< 0.001
Left cadence, m/min	138.29 ± 22.40	145.55 ± 20.85	140.21 ± 22.83	134.54 ± 19.71	129.47 ± 19.89	131.19 ± 18.75	< 0.001
Right cadence, m/min	137.08 ± 22.49	144.33 ± 24.57	138.02 ± 19.86	133.73 ± 20.40	128.67 ± 20.63	132.45 ± 21.01	< 0.001
Left stance, %	67.06 ± 3.22	66.15 ± 3.43	67.12 ± 3.16	67.22 ± 2.95	67.88 ± 2.69	68.46 ± 2.83	< 0.001
Right stance, %	66.45 ± 3.29	65.54 ± 3.35	66.36 ± 3.11	66.82 ± 3.06	67.17 ± 2.80	67.91 ± 3.19	< 0.001
Left swing, %	32.94 ± 3.22	33.85 ± 3.43	32.88 ± 3.16	32.78 ± 2.95	32.12 ± 2.69	31.54 ± 2.83	< 0.001
Right swing, %	33.55 ± 3.29	34.46 ± 3.35	33.64 ± 3.11	33.18 ± 3.06	32.83 ± 2.8	32.09 ± 3.19	< 0.001
Double support, %	32.65 ± 5.05	30.79 ± 5.31	32.43 ± 4.44	33.35 ± 4.09	34.47 ± 3.96	35.56 ± 4.71	< 0.001
Left step height, m	0.12 ± 0.02	0.12 ± 0.02	0.12 ± 0.02	0.12 ± 0.02	0.12 ± 0.02	0.11 ± 0.02	< 0.001
Right step height, m	0.12 ± 0.02	0.12 ± 0.02	0.12 ± 0.02	0.12 ± 0.02	0.11 ± 0.02	0.10 ± 0.02	< 0.001
Step width, m	0.12 ± 0.02	0.12 ± 0.02	0.12 ± 0.02	0.12 ± 0.02	0.13 ± 0.02	0.14 ± 0.02	< 0.001
Left cycle duration, s	0.90 ± 0.15	0.86 ± 0.12	0.89 ± 0.16	0.92 ± 0.14	0.96 ± 0.15	0.94 ± 0.14	< 0.001
Right cycle duration, s	0.90 ± 0.14	0.85 ± 0.11	0.89 ± 0.13	0.92 ± 0.14	0.95 ± 0.15	0.94 ± 0.14	< 0.001
Turn time, s	1.11 ± 0.42	0.95 ± 0.31	1.08 ± 0.38	1.11 ± 0.38	1.25 ± 0.43	1.46 ± 0.59	< 0.001
Left cycle duration variability, %	9.38 ± 6.18	10.21 ± 7.42	9.18 ± 4.7	8.76 ± 5.05	9.08 ± 6.13	8.79 ± 4.31	0.004
Right cycle duration variability, %	9.80 ± 7.21	10.62 ± 9.35	9.43 ± 5.62	9.07 ± 4.95	9.2 ± 5.46	9.92 ± 8.09	0.152
Left stance variability, %	6.94 ± 4.09	7.28 ± 4.12	7.36 ± 3.92	6.67 ± 4.05	6.52 ± 4.48	6.46 ± 3.62	< 0.001

(Continued)

Table 2

(continued)

Motor parameters	Overall	18–49 years	50–59 years	60–69 years	70–79 years	> 80 years	<i>p</i>
Right stance variability, %	7.10 ± 4.17	8.18 ± 5.2	7.28 ± 4.35	6.67 ± 3.39	6.2 ± 3.53	6.68 ± 3.04	< 0.001
Stance asymmetry, %	0.83 ± 5.73	0.62 ± 7.2	1.1 ± 5.59	0.68 ± 5	0.8 ± 5.26	1.15 ± 4.39	0.927
Left swing variability, %	14.04 ± 7.81	14.18 ± 8.17	14.93 ± 8.05	13.54 ± 7.74	13.34 ± 7.14	14.07 ± 7.43	0.012
Right swing variability, %	13.90 ± 7.52	15.33 ± 9.04	14.17 ± 7.75	13.24 ± 6.59	12.46 ± 6.28	14.07 ± 6.46	< 0.001
Swing asymmetry, %	−1.82 ± 10.68	−1.86 ± 11.31	−2.21 ± 10.96	−1.27 ± 11.12	−1.81 ± 9.15	−2.32 ± 9.4	0.891
Double support variability, %	19.87 ± 14.77	23.6 ± 16.45	20.82 ± 14.66	18.18 ± 12.86	16.42 ± 12.5	18.84 ± 17.47	< 0.001
Step width variability, %	10.89 ± 5.74	11.58 ± 6.06	11.03 ± 6.03	11.03 ± 5.95	10.3 ± 4.41	9.23 ± 5.22	< 0.001
Left stride length variability, %	14.74 ± 10.19	15.78 ± 11.34	14.45 ± 9.71	14.6 ± 10.11	14.26 ± 10.02	14.11 ± 8.5	0.682
Right stride length variability, %	16.04 ± 10.49	17.97 ± 12.54	16.56 ± 10.89	14.77 ± 9.25	15.46 ± 9.27	14.19 ± 7.82	< 0.001
Stride length asymmetry, %	0.69 ± 11.10	0.79 ± 14.58	0.82 ± 11.7	0.33 ± 9.12	0.68 ± 8.86	1.21 ± 7.02	0.947
Left step height variability, %	34.24 ± 12.02	34.88 ± 12.5	34.31 ± 11.77	33.86 ± 11.97	34.54 ± 11.59	32.83 ± 12.43	0.241
Right step height variability, %	37.52 ± 12.69	37.16 ± 11.93	38.85 ± 12.7	37.21 ± 12.25	37.08 ± 12.65	36.4 ± 15.74	0.018
Step height asymmetry, %	5.79 ± 19.12	4.67 ± 20.45	7.3 ± 18.86	6.08 ± 17.95	4.03 ± 18.8	7.19 ± 20	0.140
Left cadence variability, %	14.54 ± 9.38	15.74 ± 7.83	15.14 ± 14.32	13.89 ± 7.01	13.69 ± 6.49	13.22 ± 5.23	< 0.001
Right cadence variability, %	13.85 ± 9.94	16.08 ± 16.86	13.46 ± 6.44	13.28 ± 6.74	12.29 ± 5.22	13.64 ± 6.31	< 0.001
Cadence asymmetry, %	0.62 ± 8.86	0.84 ± 9.63	1 ± 9.51	0.22 ± 8.18	0.91 ± 7.66	−0.41 ± 9	0.399
Left stride speed variability, %	14.46 ± 7.33	14.87 ± 8.06	14.01 ± 7.36	14.38 ± 6.89	14.52 ± 6.89	14.8 ± 7.33	0.520
Right stride speed variability, %	15.04 ± 7.66	15.89 ± 8.79	15.43 ± 8.1	13.94 ± 6.46	15.04 ± 7.07	14.96 ± 7.19	0.035
Stride speed asymmetry, %	−0.08 ± 10.42	0.15 ± 13.03	0.32 ± 11.95	−0.68 ± 7.82	−0.52 ± 8.18	0.96 ± 8.27	0.111
Left cycle duration variability, %	9.3 ± 6.19	10.25 ± 7.53	9.26 ± 4.74	8.93 ± 6.17	9.41 ± 6.68	8.7 ± 4.33	0.002
Right cycle duration variability, %	9.76 ± 7.17	10.62 ± 9.43	9.7 ± 6.6	9.23 ± 5.52	9.55 ± 6.27	9.6 ± 7.61	0.176
Cycle duration asymmetry, %	0.67 ± 7.11	0.52 ± 8.29	0.59 ± 7.78	0.66 ± 6.29	1.23 ± 5.99	0.27 ± 5.86	0.218

when performing the test was more evident. Female participants had a higher degree of sway when performing natural standing and straight-line walking and a longer duration to complete the timed up-and-go (TUG) test. In addition, female participants demonstrated higher variability in many parameters than men. There was no between-sex difference in gait speed (1.17 ± 0.25 m/s vs. 1.17 ± 0.26 m/s, $p = 0.964$), but male participants

had a slower stride frequency, longer stride length, and a higher step height compared to female participants. Regarding gait cycle parameters, male participants had longer stance and double-support phases. A higher education level was associated with a shorter total duration in the rapid hand pronation–supination and TUG tests and a smaller degree of sway in straight-line walking and 5-times sit-to-stand test. A higher education

Table 3: Motor parameters, stratified by sex and educational level.

Motor parameters	Male	Female	<i>p</i> value	Junior high school and below	High school and above	<i>p</i> value
Right hand pronation–supination, s	8.92 ± 2.75	8.75 ± 2.23	0.362	9.05 ± 2.53	8.53 ± 2.40	< 0.001
Left hand pronation–supination, s	9.39 ± 2.74	9.31 ± 2.66	0.564	9.63 ± 2.87	8.96 ± 2.39	< 0.001
5 times sit-to-stand, s	12.95 ± 3.28	12.57 ± 3.20	0.009	12.72 ± 3.25	12.79 ± 3.24	0.479
5 times sit-to-stand: sway, %	31.29 ± 7.07	28.58 ± 6.68	< 0.001	30.15 ± 6.89	29.43 ± 7.12	0.022
Natural standing: sway, %	11.65 ± 6.57	11.77 ± 5.36	0.017	11.83 ± 6.3	11.56 ± 5.46	0.605
Parallel standing: sway, %	11.69 ± 6.13	11.46 ± 5.37	0.969	11.67 ± 5.71	11.43 ± 5.78	0.412
Semi-tandem standing: sway, %	12.06 ± 5.65	12.20 ± 5.94	0.905	12.21 ± 5.98	12.03 ± 5.56	0.766
Tandem standing: sway, %	13.72 ± 5.89	13.57 ± 5.73	0.646	13.80 ± 5.77	13.42 ± 5.86	0.146
Straight-line walking, s	12.29 ± 3.58	12.37 ± 3.86	0.615	12.28 ± 3.71	12.40 ± 3.75	0.232
Straight-line walking: sway, %	20.44 ± 7.48	21.65 ± 8.41	0.002	21.69 ± 8.47	20.27 ± 7.26	< 0.001
Timed up and go, s	12.58 ± 3.18	12.19 ± 3.04	0.005	12.52 ± 3.14	12.16 ± 3.08	0.004
Gait speed, m/s	1.17 ± 0.25	1.17 ± 0.26	0.964	1.15 ± 0.25	1.19 ± 0.26	0.001
Left stride length, m	1.15 ± 0.18	1.08 ± 0.18	< 0.001	1.10 ± 0.19	1.13 ± 0.18	0.002
Right stride length, m	1.14 ± 0.17	1.07 ± 0.16	< 0.001	1.09 ± 0.18	1.12 ± 0.16	< 0.001
Left stride speed, m/s	1.25 ± 0.27	1.24 ± 0.26	0.147	1.23 ± 0.26	1.27 ± 0.26	0.004
Right stride speed, m/s	1.25 ± 0.26	1.24 ± 0.25	0.349	1.23 ± 0.25	1.27 ± 0.26	< 0.001
Left cadence, m/min	132.93 ± 21.03	141.27 ± 21.18	< 0.001	136.88 ± 22.04	138.04 ± 20.77	0.210
Right cadence, m/min	131.20 ± 19.25	140.79 ± 23.36	< 0.001	135.36 ± 20.65	137.58 ± 23.79	0.161
Left stance, %	67.45 ± 2.67	66.90 ± 3.49	< 0.001	67.2 ± 3.11	67.10 ± 3.20	0.404
Right stance, %	66.94 ± 2.91	66.22 ± 3.38	< 0.001	66.74 ± 3.24	66.31 ± 3.10	0.019
Left swing, %	32.55 ± 2.67	33.10 ± 3.49	< 0.001	32.80 ± 3.11	32.90 ± 3.20	0.404
Right swing, %	33.06 ± 2.91	33.78 ± 3.38	< 0.001	33.26 ± 3.24	33.69 ± 3.10	0.019
Double support, %	33.65 ± 4.08	32.24 ± 5.19	< 0.001	33.09 ± 4.65	32.63 ± 4.88	0.080
Left step height, m	0.13 ± 0.02	0.11 ± 0.02	< 0.001	0.12 ± 0.02	0.12 ± 0.02	0.568
Right step height, m	0.12 ± 0.02	0.11 ± 0.02	< 0.001	0.12 ± 0.02	0.12 ± 0.02	0.087
Step width, m	0.13 ± 0.02	0.12 ± 0.02	< 0.001	0.12 ± 0.02	0.12 ± 0.02	0.643
Left cycle duration, s	0.94 ± 0.15	0.88 ± 0.14	< 0.001	0.91 ± 0.14	0.91 ± 0.15	0.439
Right cycle duration, s	0.93 ± 0.14	0.88 ± 0.13	< 0.001	0.91 ± 0.14	0.90 ± 0.14	0.159
Turn time, s	1.13 ± 0.44	1.11 ± 0.4	0.605	1.12 ± 0.39	1.12 ± 0.46	0.068
Left cycle duration variability, %	8.58 ± 4.55	9.86 ± 6.61	< 0.001	9.36 ± 5.76	9.13 ± 5.79	0.055
Right cycle duration variability, %	8.95 ± 5.24	10.2 ± 7.8	< 0.001	9.67 ± 7.55	9.54 ± 5.49	0.444
Left stance variability, %	6.52 ± 3.54	7.31 ± 4.48	0.00016	6.84 ± 3.84	7.08 ± 4.41	0.642287
Right stance variability, %	6.68 ± 3.77	7.46 ± 4.46	0.000047849	7.05 ± 4.34	7.16 ± 3.93	0.408175
Stance asymmetry, %	0.84 ± 4.63	0.82 ± 6.54	0.988286	0.76 ± 6	0.92 ± 5.35	0.593831
Left swing variability, %	13.47 ± 7.19	14.54 ± 8.29	0.002838	13.92 ± 7.46	14.21 ± 8.27	0.930864

(Continued)

Table 3

(continued)

Motor parameters	Male	Female	<i>p</i> value	Junior high school and below	High school and above	<i>p</i> value
Right swing variability, %	13.42 ± 7.38	14.31 ± 7.63	0.005007	13.82 ± 7.32	14.01 ± 7.78	0.898898
Swing asymmetry, %	−1.62 ± 9.28	−1.99 ± 11.77	0.98603	−1.73 ± 11.11	−1.93 ± 10.08	0.663333
Double support variability, %	17.62 ± 13.19	21.84 ± 15.77	3.3801E−10	19.56 ± 14.56	20.28 ± 15.04	0.697839
Step width variability, %	10.51 ± 5.55	11.22 ± 5.88	0.012947	10.76 ± 5.95	11.06 ± 5.44	0.023607
Left stride length variability, %	14.21 ± 9.28	15.21 ± 10.9	0.198619	14.6 ± 10.28	14.94 ± 10.06	0.459603
Right stride length variability, %	15.78 ± 9.28	16.26 ± 11.45	0.753443	15.69 ± 10.29	16.5 ± 10.75	0.066297
Stride length asymmetry, %	0.87 ± 9	0.54 ± 12.66	0.574033	0.99 ± 10.46	0.28 ± 11.91	0.089605
Left step height variability, %	33.14 ± 11.26	35.2 ± 12.58	0.002205	33.99 ± 11.86	34.57 ± 12.24	0.269586
Right step height variability, %	36.3 ± 11.84	38.58 ± 13.3	0.001027	37.83 ± 12.97	37.09 ± 12.28	0.162376
Step height asymmetry, %	5.3 ± 18.67	6.22 ± 19.5	0.40825	6.53 ± 19.03	4.8 ± 19.21	0.042436
Left cadence variability, %	14.06 ± 7.3	14.97 ± 10.87	0.022162	14.4 ± 7.36	14.74 ± 11.57	0.934851
Right cadence variability, %	13 ± 6.38	14.59 ± 12.19	0.000034688	13.33 ± 6.42	14.55 ± 13.25	0.112497
Cadence asymmetry, %	0.79 ± 8.53	0.48 ± 9.14	0.209866	0.8 ± 8.66	0.38 ± 9.13	0.414911
Left stride speed variability, %	14.09 ± 7.03	14.79 ± 7.57	0.045404	14.48 ± 7.08	14.45 ± 7.66	0.550312
Right stride speed variability, %	14.96 ± 7.36	15.11 ± 7.9	0.817008	14.86 ± 7.46	15.28 ± 7.91	0.473936
Stride speed asymmetry, %	0.12 ± 9.67	−0.24 ± 11.03	0.431682	0.16 ± 9.76	−0.39 ± 11.25	0.499342
Left cycle duration variability, %	8.64 ± 4.78	10.03 ± 7.15	0.000004266	9.55 ± 6.42	9.15 ± 5.86	0.033701
Right cycle duration variability, %	9.14 ± 5.74	10.3 ± 8.18	0.001008	9.79 ± 7.85	9.71 ± 6.13	0.275311
Cycle duration asymmetry, %	0.76 ± 5.29	0.6 ± 8.38	0.779749	0.47 ± 7.67	0.95 ± 6.27	0.455633

level was associated with a significantly faster gait speed, larger stride length, faster stride speed, longer right-swing phase, and shorter right-stance phase.

The *p*-values represented the significance of the analysis of variance (ANOVA) test conducted for inter-group comparisons between different age groups.

Supplementary table 2 presents the associations between the independent variables, namely age, sex, education level, and the 54 different motor parameters. Using the probability of non-zero association exceeding 70%, age showed a strong association with stride length, stride speed, and TUG-test completion time, and a 20-year increase in age was associated with 0.11-m slower stride length, 0.19-m/s slower stride speed, and 1.87-s longer TUG-test completion time. Changes in age did not show an effect on step width as the difference was 0.00 m

(95% CI: −0.05 to 0.04). Additionally, parameters including step height, hand pronation–supination test results, postural stability, swing time asymmetry, and cycle duration variability showed minimal differences with age. Differences in education level did not have a significant impact on any of the motor parameters with a probability of approximately 50%. After adjustment for age and education level, more than 70% of the male participants had a 0.02 m greater step height and a 0.02 m longer step width than their female counterparts. No substantial differences were observed in the posterior distributions of the other motor parameters compared with the independent variables.

Reference ranges for quantitative parameters

Figure 3 shows the predicted values and 95% CI for gait speed, TUG, step height, and step width against

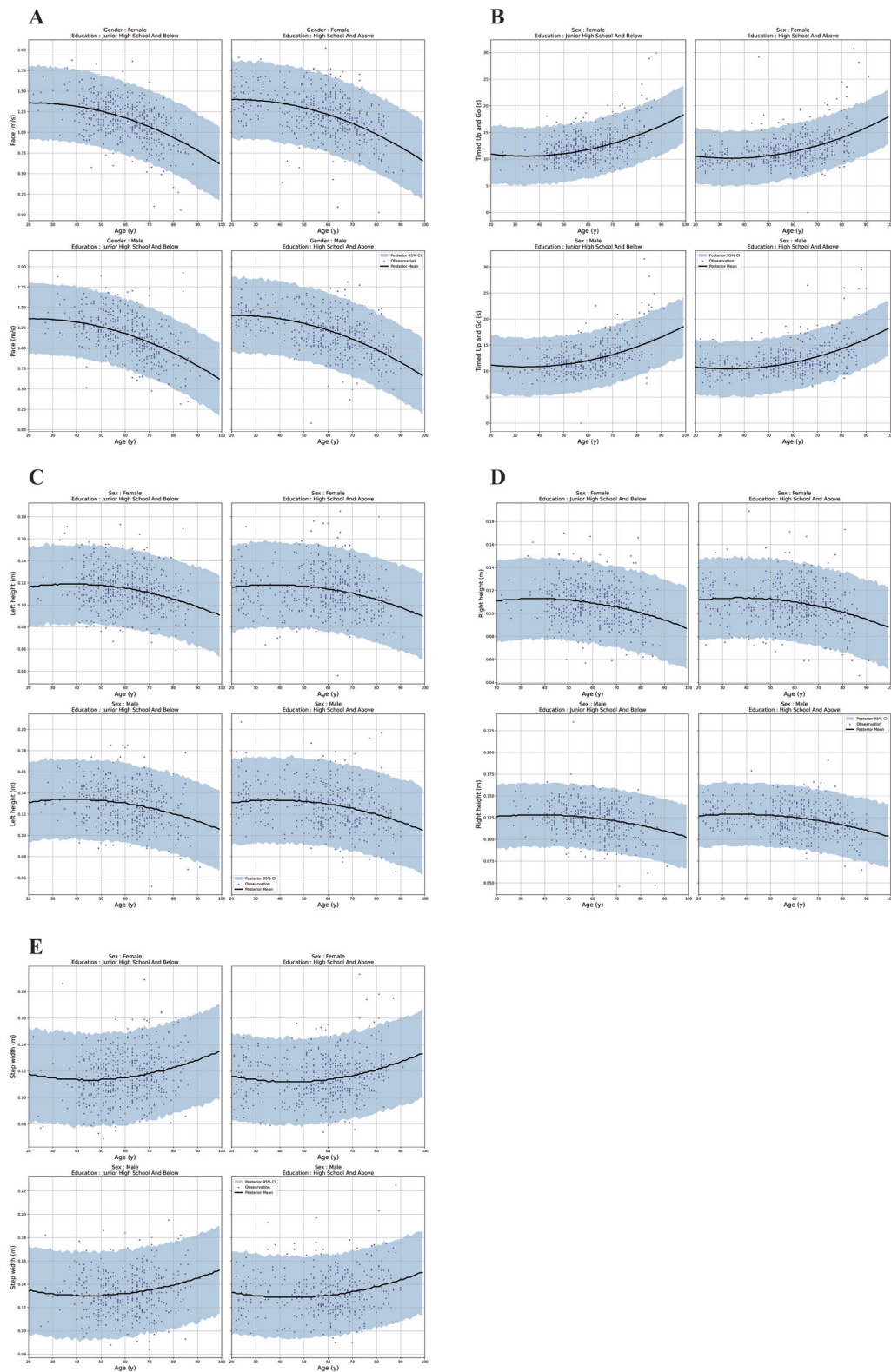


Figure 3: Reference ranges for gait speed, TUG, step height, and step width.

Predicted values and 95% reference ranges of gait speed (A), time to finish the TUG test (B), left step height (C), right step height (D), and step width (E). Multivariable Bayesian linear regression (BLR) models were adjusted for age and stratified by sex and education level. The solid black line represents the predicted value obtained from BLR, the shaded blue range represents the 95% confidence interval, and the scattered points represent the actual observed values. TUG: timed up-and-go.

age, stratified by sex and education level. The reference ranges for the remaining 49 motor parameters are shown in supplementary material Figure 1.

An interactive web-based application (testcog2b.ruiyicas.com:8099) was developed to explore the subgroup-specific predicted values and reference ranges. By entering the corresponding parameters in this application, we estimated that the predicted gait speed for female participants aged 60 with a junior high school education, as calculated by our model, was 1.17 m/s (95% CI: 0.74–1.58 m/s). In contrast, for men of the same age with senior high school education, the predicted value of gait speed was 1.21 m/s (95% CI: 0.76–1.64 m/s).

Test-retest performance evaluation of quantitative parameters

A total of 202 participants were selected for re-evaluation, and the results of the retesting agreement and reliability analyses are presented in Table 4. The Bland–Altman analysis revealed that the differences between the two tests for all motor parameters were relatively small, with more than 95% of the differences falling within the limits of the agreement confidence interval. The ICC for the 5-times sit-to-stand completion time and sway degree, TUG-test completion time, gait speed, stride speed, and step width exceeded 0.5, indicating moderate reliability. However, ICC for other parameters ranged between 0.2 and 0.5, indicating poor reliability.

Table 4: Test-retest reliability evaluation of motor function.

Motor parameters	Agreement			Reliability		
	Diff-mean	Diff-Std	LOA	Numbers (percent) of measurements within LOA	ICC (95% CI)	<i>p</i>
Right hand pronation–supination, s	0.02	0.44	−0.96, 0.99	175 (87.50%)	0.36 (0.23, 0.47)	–
Left hand pronation–supination, s	0.56	2.21	−4.28, 5.41	190 (95.00%)	0.36 (0.23, 0.48)	< 0.001
5 times sit-to-stand, s	−0.22	2.63	−6.00, 5.56	193 (96.50%)	0.55 (0.45, 0.64)	< 0.001
5 times sit-to-stand: sway, %	−0.10	5.73	−12.69, 12.49	193 (96.50%)	0.64 (0.55, 0.71)	< 0.001
Natural standing: sway, %	0.16	5.66	−12.29, 12.60	194 (97.00%)	0.45 (0.33, 0.55)	< 0.001
Parallel standing: sway, %	0.18	7.22	−15.69, 16.05	194 (97.00%)	0.28 (0.15, 0.40)	< 0.001
Semi–tandem standing: sway, %	0.37	6.38	−13.65, 14.38	195 (97.50%)	0.31 (0.18, 0.43)	< 0.001
Tandem standing: sway, %	0.67	6.57	−13.76, 15.09	196 (98.00%)	0.37 (0.24, 0.48)	< 0.001
Straight–line walking, s	0.01	2.84	−6.23, 6.26	194 (97.00%)	0.54 (0.43, 0.63)	< 0.001
Straight–line walking: sway, %	−0.49	8.88	−19.99, 19.01	191 (95.50%)	0.27 (0.14, 0.40)	< 0.001
Timed Up and Go, s	−0.35	2.33	−5.47, 4.78	195 (97.50%)	0.60 (0.50, 0.68)	< 0.001
Gait speed, m/s	0.00	0.23	−0.50, 0.51	190 (95.48%)	0.60 (0.50, 0.68)	< 0.001
Left stride length, m	−0.02	0.22	−0.50, 0.45	192 (96.48%)	0.45 (0.33, 0.55)	< 0.001
Right stride length, m	0.01	0.13	−0.28, 0.31	194 (97.49%)	0.62 (0.52, 0.70)	< 0.001
Left stride speed, m/s	−0.02	0.24	−0.55, 0.52	190 (95.48%)	0.54 (0.43, 0.63)	< 0.001
Right stride speed, m/s	0.01	0.23	−0.50, 0.51	190 (95.48%)	0.57 (0.47, 0.66)	< 0.001
Left cadence, m/min	−0.58	21.49	−47.80, 46.64	189 (94.97%)	0.42 (0.30, 0.53)	< 0.001
Right cadence, m/min	−0.61	21.90	−48.73, 47.50	187 (93.97%)	0.53 (0.42, 0.62)	< 0.001
Left stance, %	0.01	4.30	−9.45, 9.47	191 (95.98%)	0.20 (0.07, 0.33)	0.002
Right stance, %	0.20	3.55	−7.60, 8.01	188 (94.47%)	0.37 (0.24, 0.48)	< 0.001

(Continued)

Table 4

(continued)

Motor parameters	Agreement			Reliability		
	Diff-mean	Diff-Std	LOA	Numbers (percent) of measurements within LOA	ICC (95% CI)	<i>p</i>
Left swing, %	−0.01	4.30	−9.47, 9.45	191 (95.98%)	0.20 (0.07, 0.33)	0.02
Right swing, %	−0.20	3.55	−8.01, 7.60	188 (94.47%)	0.37 (0.24, 0.48)	< 0.001
Double support, %	0.36	5.51	−11.76, 12.48	188 (94.47%)	0.28 (0.14, 0.40)	< 0.001
Left step height, m	−0.00	0.02	−0.05, 0.05	192 (96.48%)	0.40 (0.28, 0.51)	< 0.001
Right step height, m	−0.00	0.02	−0.05, 0.04	193 (96.98%)	0.43 (0.31, 0.53)	< 0.001
Step width, m	−0.00	0.01	−0.04, 0.03	193 (96.98%)	0.70 (0.61, 0.76)	< 0.001
Left cycle duration, s	−0.00	0.14	−0.32, 0.31	191 (95.98%)	0.47 (0.35, 0.57)	< 0.001
Right cycle duration, s	0.01	0.12	−0.25, 0.27	190 (95.48%)	0.57 (0.47, 0.66)	< 0.001
Turn time, s	−0.02	0.40	−0.90, 0.85	191 (95.98%)	0.31 (0.18, 0.43)	< 0.001
Left cycle duration variability, %	0.30	8.43	−18.23, 18.82	190 (95.48%)	0.27 (0.03, 0.45)	0.014
Right cycle duration variability, %	−0.38	7.01	−15.78, 15.03	193 (96.98%)	0.44 (0.26, 0.58)	< 0.001
Left stance variability, %	0.28	5.66	−12.17, 12.73	190 (95.00%)	0.062 (−0.24, 0.291)	0.325
Right stance variability, %	−0.23	4.87	−10.93, 10.48	193 (96.50%)	0.307 (0.084, 0.476)	0.005
Stance asymmetry, %	−0.09	6.85	−15.14, 14.96	192 (96.00%)	0.146 (−0.13, 0.354)	0.134
Left swing variability, %	0.65	11.77	−25.20, 26.50	193 (96.50%)	−0.012 (−0.338, 0.234)	0.534
Right swing variability, %	−0.33	9.32	−20.81, 20.14	194 (97.00%)	0.278 (0.045, 0.454)	0.011
Swing asymmetry, %	0.32	14.59	−31.75, 32.38	193 (96.50%)	0.154 (−0.12, 0.36)	0.121
Double support variability, %	−0.07	18.98	−41.77, 41.62	194 (97.00%)	0.432 (0.248, 0.57)	< 0.001
Step width variability, %	0.50	7.20	−15.32, 16.32	191 (95.50%)	0.212 (−0.041, 0.404)	0.047
Left stride length variability, %	2.68	16.12	−32.74, 38.10	192 (96.00%)	0.029 (−0.274, 0.261)	0.415
Right stride length variability, %	−0.74	13.75	−30.94, 29.46	194 (97.00%)	0.161 (−0.109, 0.366)	0.108
Stride length asymmetry, %	−1.93	14.31	−33.38, 29.52	191 (95.50%)	0.072 (−0.221, 0.295)	0.297
Left step height variability, %	1.65	15.06	−31.45, 34.74	190 (95.00%)	0.471 (0.302, 0.599)	< 0.001
Right step height variability, %	1.22	15.59	−33.02, 35.46	193 (96.50%)	0.318 (0.1, 0.484)	0.004
Step height asymmetry, %	−0.39	23.26	−51.49, 50.71	195 (97.50%)	0.329 (0.113, 0.493)	0.003
Left cadence variability, %	−0.91	10.35	−23.65, 21.83	192 (96.00%)	0.193 (−0.065, 0.389)	0.065
Right cadence variability, %	0.17	8.89	−19.37, 19.70	188 (94.00%)	0.253 (0.012, 0.436)	0.02
Cadence asymmetry, %	0.67	13.32	−28.60, 29.93	191 (95.50%)	−0.066 (−0.41, 0.193)	0.674
Left stride speed variability, %	1.84	10.22	−20.61, 24.30	193 (96.50%)	0.155 (−0.109, 0.356)	0.113
Right stride speed variability, %	−0.33	10.06	−22.44, 21.78	191 (95.50%)	0.258 (0.018, 0.439)	0.018
Stride speed asymmetry, %	−1.03	12.39	−28.24, 26.18	193 (96.50%)	−0.013 (−0.338, 0.233)	0.537
Left cycle duration variability, %	0.27	8.39	−18.17, 18.71	191 (95.50%)	0.278 (0.045, 0.454)	0.011
Right cycle duration variability, %	−0.59	6.56	−15.02, 13.83	193 (96.50%)	0.474 (0.306, 0.602)	< 0.001
Cycle duration asymmetry, %	−0.70	8.01	−18.30, 16.90	192 (96.00%)	0.109 (−0.177, 0.325)	0.209

Diff: Difference between two tests, defined as bias in the Bland–Altman analysis.

LOA: Expected range that includes 95% of future differences between two tests.

Std: standard deviation; ICC: intraclass correlation coefficient; CI: confidence interval.

Discussion

In this nationwide multicenter study, we established reference ranges for 54 motor parameters in adults over 18 years of age using a non-contact, 3D camera-based motion-analysis system. Multivariate BLR models were used to derive 95% CIs as reference ranges, including age, sex, and education level as independent variables. The design of motions was based on traditional clinical scales, including the SARA^[13], Short Physical Performance Battery (SPPB)^[16], UPDRS^[14], and Tinetti^[15] scales, covering tests that evaluate motor ability in the normal older population and patients with motor disorders of Parkinsonism or ataxia. The extracted parameters included upper-limb movements, gait features, and posture stability, which provided a relatively comprehensive evaluation of motor function during a walking cycle.

In recent years, gait analysis has gained increasing recognition owing to its clinical utility in the diagnosis and monitoring of various diseases. Currently, clinical motor assessments rely predominantly on qualitative descriptions of gait patterns and semiquantitative assessment scales, which are inherently subjective and difficult to detect.^[18] Instrumented gait analysis (IGA) provides clinicians with accurate and reliable motor parameters across various dimensions, which not only assist in the construction of diagnostic models but also allows for traditional diagnosis of diseases characterized by motor disorders. Reference ranges, norms, and standard procedures must be established^[19]. Previous studies that established reference values for motor parameters predominantly relied on one-dimensional data collection^[20–22], focusing on gait speed and test completion time. 2D IGA, incorporating force plates, electronic walkways, and treadmills^[23,24], extends parameter collection to include stride length and width, cadence, and gait-cycle duration and variability. However, it cannot capture 3D spatial and posture parameters (e.g., step height and posture stability), as well as upper-limb data. Wearable sensing systems and artificial intelligence-driven computational platforms enable the acquisition of 3D parameters that complement conventional spatio-temporal parameters. Studies have demonstrated that wearable sensing systems face limitations related to device wearability and low compliance. To enable a more comprehensive and practically applicable clinical

approach for motor assessment, we integrated a non-contact, depth-based 3D camera with a deep learning-based motion-analysis system. This system can collect data on a wide spectrum of motor parameters, including upper-limb mobility, gait parameters, and postural stability. Multiple aspects of motor function have the potential to further identify individual phenotypes, offering valuable insights that can guide clinical treatment approaches and enhance our understanding of disease progression.

Our findings should be interpreted in the context of previous normative studies conducted in other populations. Several studies have established reference data for gait and motor parameters using markerless RGB-depth cameras, inertial sensors, or laboratory-based three-dimensional motion-capture systems. For example, normative data for 43 spatiotemporal motor parameters were established in healthy adults using an RGB-depth camera system^[25], while a large European dataset of 246 healthy adults aged 18–91 years provided three-dimensional gait data across different walking speeds^[26]. Normative gait data have also been reported in Singaporean and Malaysian populations^[27,28]. However, direct comparison across studies is challenging because of differences in population characteristics, age distribution, walking protocols, measurement technologies, and definitions of motor parameters. Our study complements these efforts by providing multicenter normative data across a broad age range in Chinese adults using a standardized 3D motion-analysis system and by extending the reference framework to 54 motor parameters.

Walking speed is the most widely studied quantitative motor parameter and is usually assessed through timed walking in natural scenarios or on a walkway system. Our study observed an overall higher gait speed (1.18 m/s) compared to the Singaporean population (1.06 m/s)^[24]. However, the gait speed of individuals over 60 years of age was lower than that of the older Japanese population (1.29 m/s in men and 1.25 m/s in female participants)^[21] and that of the population in Western countries (1.20 m/s)^[20]. Gao et al.^[29] investigated reference ranges for the 5-times sit-to-stand test in Chinese adults and found the completion time (ranging from 5.57 s to 14.58 s) across age groups from 50 to 54 years in men, which was generally consistent with our study's findings (ranging from 5.53 s to 18.04 s) in

the same age groups. We found stability in all parameters between the ages of 20 and 50 years, after which changes became apparent as age increased, with the most pronounced changes observed in the stride length, stride speed, and completion time of the TUG test. This pattern aligns with previous findings^[24,30], underscoring that motor function may decline gradually after reaching one's fifties. This decline can be attributed to reduced joint coordination, muscle mass, and bone density, leading to diminished control of the hip and ankle joint movements. In contrast, step width, step height, hand pronation–supination test, and postural stability exhibited minimal changes as age increased from 50 to 70 years. Therefore, a noteworthy decline in these aspects should raise concerns and prompt alerts about potential motor disorders. In agreement with previous findings^[24], men walked with a larger step width and height than female participants. Beyond the variables directly linked to motor function such as sex and age, we also incorporated education level as an independent variable in our BLR model. Prior research has suggested a correlation between higher education attainment, increased maximum gait speed^[31], and larger stride length^[32]. In contrast to some previous studies, we did not observe strong associations between education level and most motor parameters. Several factors may explain this discrepancy. First, education was categorized into two broad groups to ensure adequate sample sizes across the reference strata, which may have attenuated more subtle associations. Second, education may partly reflect socioeconomic circumstances, occupational exposures, and lifestyle factors, which were not comprehensively captured in our study. Therefore, the absence of an observed association should not be interpreted as evidence that socioeconomic or educational factors have no influence on motor performance. Further studies are required to explore the potential impact of education level on motor parameters.

Our study showed overall good test-retest agreement, as evidenced by the Bland–Altman analysis, revealing small differences between the two tests. The good agreement suggests that the measured motor parameters were consistent and had low systematic bias between the two tests. Therefore, we demonstrated that the uniform motor collection procedures used in our study, along with the parameters obtained from the motion-analysis

system, maintained agreement between the two tests. The ICC for the 5-times sit-to-stand completion time and sway degree, TUG-test completion time, gait speed, stride speed, and step width exceeded 0.5, indicating moderate reliability^[33]. However, we also observed poor test-retest reliability for certain parameters, with ICC ranging from 0.2 to 0.5. Reliability depends on both the between-participant variance and measurement error and is generally considered as the variance between participants/ (variance between participants + measurement error). Therefore, the reliability could be low when the between-participant variance is small compared to the measurement error^[17]. Since our study recruited participants with normal motor function, the between-participant differences may have been small for some parameters. This may partly explain the low reliability of some parameters. In consideration of clinical application, parameters with good reliability are more capable of effectively monitoring or differentiating the diagnosis of associated diseases. However, studies in patients with certain diseases are still necessary as the motor parameters may change significantly, and the reliability of some parameters might be fair under these circumstances.

The strength of this study is that we derived reference ranges for 54 motor parameters, extending beyond the conventional focus on metrics including gait speed^[20] and the 5-times sit-to-stand tests. Moreover, rather than calculating reference data based on age-stratified groups^[20,21,24], we fit the BLR regression models for continuous reference ranges across the age spectrum. The BLR model not only effectively managed the non-linear relationship between independent variables and motor parameters, but also generated continuous reference ranges for motor parameters across the age spectrum. This approach enhances the clinical utility and relevance of reference ranges.

Our results provide a benchmark for the early diagnosis of neurological diseases and motor disorders. Ataxic gait is clinically characterized by a wide-based stance. In a meta-analysis^[34] comprising 192 patients with cerebellar ataxia, the observed step width was 0.17 ± 0.04 m. Utilizing the average step width of 0.12 ± 0.02 m among normal adults as a reference in our study, cerebellar ataxia can be objectively and quantitatively

identified. Previous studies^[35,36] also suggested that a higher total cerebral small vascular disease burden was correlated with reduced gait speed and stride length. Motion-analysis techniques can quantify subtle motor abnormalities that might be neglected using current clinical methods.

Our study has several limitations. First, as physical performance may differ across various populations and be affected by culture and ethnicity^[22], our results can only be applied to the Chinese population. Second, height was not included as an independent variable in the BLR model. Although height may influence several motor parameters, particularly spatial gait parameters, the available evidence at the study-design stage was insufficient to define appropriate and clinically meaningful height-specific strata across the broad range of motor parameters assessed in this study. We therefore prespecified age, sex, and education level as the primary stratification factors, with sex partially capturing population-level differences in body stature. Nevertheless, sex cannot fully account for individual variation in height, and residual confounding related to body stature may remain. Future studies with larger and more representative Chinese populations are warranted to more precisely characterize the associations between height and individual motor parameters and to establish height-specific normative ranges. Third, although participants were recruited from 13 hospitals distributed across six major geographical regions of China, regional heterogeneity related to urbanization, socioeconomic status, healthcare accessibility, and other contextual factors could not be fully accounted for because detailed and consistently collected individual-level socioeconomic and residential information was unavailable across all participating centers. Therefore, residual regional heterogeneity may remain and should be further evaluated in future population-based studies. Fourth, although participants underwent self-reported health screening, general consultation, physical examination, and cognitive assessment, subclinical or very early neurological, musculoskeletal, or systemic conditions that do not produce clinically apparent symptoms could not be completely excluded. Fifth, although standardized testing procedures and instructions were implemented across participating centers, testing time and environmental conditions, including temperature, lighting, and

background noise, were not systematically recorded or strictly standardized. These factors may have introduced some variability in motor performance and could not be accounted for in the analyses. Future studies should systematically record and standardize these conditions to further improve the reproducibility and comparability of quantitative motor assessments.

Conclusion

In conclusion, rapidly emerging technologies, including smart wearable technology, sensor-fusion approaches, and artificial intelligence-driven computational platforms, are increasingly attracting greater attention in motor assessment. Standardization of clinical protocols is critical for quantitative motor assessment in clinical practice. We provided subgroup-specific reference ranges for various motor parameters and affirmed the agreement and clinical use of a protocol involving uniform procedures and a gait recognition system based on a three-dimensional video camera. Further studies are needed to determine the threshold value for distinguishing between different motor disorders.

Author contributions

Y-CZ conceived the study and acquired the funding. D-DZ, X-HH and J-XZ carried out clinical research, analyzed clinical data, and wrote the paper. NS, KW, Z-ZL, Y-MX, YX, L-HW, BW, BH, Y-ZW, HJ, Z-QL, LC, JW, JY, FH, BS, and CY carried out clinical research and collected clinical samples. X-CZ, WS, Y-CJ, FT, and X-MF analyzed clinical data and drew the three pictures.

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Ethics statement

This study was approved by the Ethics Committee of Peking Union Medical College Hospital, China (HS-3076). The research was conducted in accordance with the Declaration of Helsinki to protect the subjects. All participants signed an informed consent form.

Data availability statement

Access to the data gathered for this study, along with the data dictionary and deidentified participant information, is limited to external researchers who submit relevant project proposals upon contacting the corresponding author. Following the approval of the proposal and the completion of a signed data access/sharing agreement, the data will be made accessible upon publication.

AI statement

The authors declare that no generative artificial intelligence (AI) or AI-assisted technologies were used in the preparation, analysis, writing, image generation, or image processing of this manuscript.

Conflicts of interest

The authors declare no conflicts of interest.

Supplementary files

Supplementary material is available in the online version of this article at <https://doi.org/10.15302/HB.2026.0008> and is accessible for authorized users.

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