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Spatiotemporal gait parameters for older adults – An interactive model adjusting reference data for gender, age, and body height

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ABSTRACT

Introduction: Since it is well documented that spatiotemporal gait parameters are affected by body size, it is of limited clinical value to compare individual scores against reference values without taking body size into consideration. For older adults, reference values have been presented in recent reports, but unfortunately the effect of body size on gait characteristics was not taken into account and neither prediction intervals nor percentile ranks were included. It is the aim of this study to present and assess a model where individual spatiotemporal gait parameter values for older adults can be compared to reference values adjusted for gender, age, and body height.

Methods: Reference gait data were collected from 1464 older adults aged 69–80 years with no impairments believed to affect gait, stratified by gender, intermediately adjusted to a common body height using a pendulum model and entered into a simple regression model for each parameter with age as predictor. From the regression coefficients predicted gait parameter values could be back transformed to the individual body height of a new subject. Calculations were done using spreadsheet formulae and equations.

Results: A spreadsheet based graphical user interface (GUI) has been developed in Microsoft Excel® where individual spatiotemporal gait data is entered for comparison with reference data taking gender, age and body height into account, and returning predicted point estimates with confidence intervals, prediction intervals, and percentile ranks.

Significance: A GUI solution where individual spatiotemporal gait data is compared to reference data is feasible to researchers and for clinical use. To the best of our knowledge, this is the first model presented for comparison of basic gait parameters between individuals and reference data from older adults where gender, age, and body height are taken into account.

1. Introduction

Normal gait is characterized by a cyclic pattern where stride length and stride time are basic spatial and temporal characteristics. From these parameters walking speed is determined as a measure of propulsion efficiency. There is a long tradition for clinical assessment of spatial and temporal gait parameters based upon timing and counting strides over a known distance. Electronic measurement systems based upon recorded footfalls allow many other spatiotemporal gait characteristics to be identified, notably by dividing the gait cycle into stance and swing phases, and further subdividing stance phase into double and single support time. However, apart from gait speed, which has a reputation as a robust generic gait parameter [1], interpretation of other spatiotemporal gait parameters is not straight forward, mainly because gait is affected by gender, age, and body size.

To help researchers and clinicians interpret results, data from a reference population against which a measurement can be compared, are of importance. In studies designed to obtain reference data, methodologic issues need careful attention [2]. Öberg et al. [3] presented reference data for basic gait parameters at slow, normal and fast gait speed for normal men and women separately, 10–79 years of age, but did not take phenotype into consideration. In a study of differences in gait scores at preferred walking speed in healthy subjects at an age range of 19–90 years, Samson et al. [4] demonstrated that gender, age and also body height contributed to differences between subjects. These results are not surprising, since gender and age effects on gait are generally

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acknowledged and supported by a host of studies, and the effect of body size on spatiotemporal gait variables is obvious by observation and strongly documented by studies taking body size into consideration [5–8].

Spatiotemporal gait parameters have been suggested to be related to body height [6,8] even if this assumption may warrant modifications in elderly persons where body height is reduced by osteoporosis or kyphosis of the spine without a similar reduction in leg length. In such cases a more valid assumption might be that spatiotemporal gait parameters are related to leg length rather than body height. However, leg length may not always be reported and if reported, may not be measured reliably. Body height on the other hand, is more readily available from health data sources and self-reports, and may easily be measured by a stadiometer, and has been shown to correlate highly with leg length [8].

For older adults, reference spatiotemporal gait data have been presented in two recent reports. Hollman et al. [9] included persons aged 70–89 without morbidities that affect gait and presented data in age strata of five years (70–74, 75–79,80−84, ≥85), while Beauchet et al. [10] included healthy older adults aged 65+ and presented data in age strata of ten years (65–74, 75–84, ≥85). In both reports reference values were reported separately for men and women, but the effect of body size on gait characteristics was not taken into account.

Since it is well documented that spatiotemporal gait parameters are affected by body size, it is of limited clinical value to compare individual scores without taking body size into account. Therefore, body size should be considered when comparing gait variables between subjects of different body size, and also when comparing individual results against reference values.

This can be done in a series of tables where reference data are grouped by gender, age and body height, or by multiple regression models for each gender separately where reference data are entered as dependent variables with gender, age and body height as predictors. An advantage of the regression approach over traditional age strata tables is the ability of the former to predict individual values treating age as a continuous variable, and not only present group values for age strata of 5 or 10 years as in previous reports.

However, the validity of regression models depends on linearity between the dependent variable and the independent variables which has been documented for spatial gait parameters versus height but not for temporal gait parameters versus height where the square root of height is an issue [6,11]. There is a need to overcome the problem of nonlinearity and to compare individual spatiotemporal gait data against reference values treating both body height and age as continuous variables.

It is the aim of this study to present and validate a model where individual spatiotemporal gait parameter values for older adults can be compared to gender specific reference values adjusted for age and body height and to overcome the limitations of including nonlinear relationships in linear regression models. It is further an aim to present a spreadsheet-based graphical user interface (GUI) where a researcher or clinician can obtain individualized predicted values for spatiotemporal gait variables with confidence intervals, prediction intervals, and percentile ranks based upon a reference database for healthy older people where data has been adjusted to the individual characteristics of the tested person.

2. Methods

2.1. Subjects

Data to be used in the reference database were extracted from subjects participating in a population-based, randomized controlled trial examining the effect of exercise training on older persons with no impairments believed to affect gait [12] (Ethical approved by Regional Committees for Medical and Health Research Ethics, Mid Norway, approval number 2015/1797), and from the reference group of a study examining the effect of cataract surgery on balance and gait in independently living older adults (fully anonymized data). The 1464 participants (52 % women) were aged 69–80 years (mean 73 years, SD 2.3 years), see Table 1 for demographics. Participants were selected based upon adequate abilities to walk independently.

2.2. Gait analysis

Participants were instructed to walk back and forth on a 7-m GAITRite® electronic walkway (CIR Systems Inc, Havertown, Pennsylvania, USA) at their preferred walking speed. Data were registered for the middle 4.7 m and the mean values of the right and left footsteps for the two walks were used as outcomes. The following spatiotemporal gait parameters were extracted from the reference database: Stride length, Stride width, Stride time, and Stance time. Single support time was estimated as Stride time - Stance time, and Double support time as Stance time - Single support time. Cadence was estimated as 120/Stride time, and Velocity as Stride length/Stride time. In addition Walk ratio (Step length/Cadence = Stride length/(2*Cadence)) was calculated and included [8]. Since single support time and swing time are identical parameters when separate data for right and left step are not reported, swing time was not included. Stride width was included since this measure is of considerable clinical interest even if an unambiguous relation to walking function has not been well documented.

2.3. Adjusting gait parameters in the reference data base for body height

Before entering gait data from each of the two gender specific strata in separate regression models with age as a predictor, gait parameters were intermediately adjusted for body height. Following the regression analysis, height adjusted data where back transformed to the individual body height of the tested person.

Spatial gait parameters have been suggested to be proportional to body height at preferred walking speed [6,8].

Stride length (SL) for person i (SL_i) in the reference data base with body height (h_i) was adjusted (SL_{ai}) to a chosen common body height (h_a) by a transformation, obtained mathematically by

$$\mathrm{SL}_{ai} = \mathrm{SL}_i(\mathrm{h}_a/\mathrm{h}_i) \tag{1}$$

For Stride width, a similar model to (1) was applied.

Temporal gait parameters based upon time, like Stride time and Stance time, are not linearly associated with body height, but are assumed to follow the laws of a mathematical pendulum at preferred walking speed [6,11], and therefore to be related to the square root of body height.

Stride time for person i (ST_i) in the reference data base was adjusted (ST_{ai}) to a chosen common body height by a transformation, obtained mathematically by

$$ST_{ai} = ST_i\sqrt{(h_a/h_i)} \tag{2}$$

For Stance time, an equivalent model to (2) was applied. Single and Double support time at a chosen common body height was deducted from Stride time and Stance time at a chosen common body height.

Since Cadence is inversely proportional to Stride time, Cadence for person i (Cad_i) in the reference data base was adjusted to a chosen common body height (Cad_{ai}) by a transformation, obtained mathematically by

$$Cad_{ai} = Cad_i\sqrt{(h_i/h_a)} \tag{3}$$

Gait velocity [1] and Walk ratio [13] are parameters combining spatial and temporal elements and were calculated using parameters that were already adjusted to a chosen common body height. Thus for persons in the reference data base Gait velocity adjusted to a chosen common body height (V_{ai}) was estimated by

Table 1
Demographics and gait characteristics by gender (n = 1464).

	Men (n = 705)				Women (n = 759)			
	Min	Max	Mean	SD	Min	Max	Mean	SD
Age (years)	69	80	72.6	2.26	69	80	72.8	2.35
Body height (m)	1.44	1.94	1.78	0.059	1.48	1.80	1.645	0.052
Stride length (m)	0.836	1.902	1.471	0.159	0.745	1.721	1.325	0.142
Stride width (m)	0.013	0.177	0.098	0.025	0.008	0.178	0.083	0.024
Stride time (s)	0.85	1.59	1.12	0.09	0.83	1.52	1.06	0.11
Stance time (s)	0.50	1.02	0.70	0.07	0.49	1.06	0.66	0.08
Single support time (s)	0.33	0.57	0.43	0.03	0.32	0.51	0.40	0.03
Double support time (s)	0.12	0.55	0.27	0.05	0.12	0.60	0.26	0.06
Cadence (steps/min)	75.5	141.2	107.4	8.33	78.9	144.6	114.4	10.77
Velocity (m/s)	0.69	1.95	1.32	0.202	0.54	1.90	1.27	0.216

$$V_{ai} = SL_{ai}/ST_{ai} \tag{4}$$

and Walk ratio adjusted to a chosen common body height (WR_{ai}) was estimated by

$$WR_{ai} = SL_{ai}/(2{*}Cad_{ai}) \tag{5}$$

After adjusting all spatiotemporal variables in the reference data base to the conveniently chosen common body height of 1.70 m using Eq.s (1–5), simple linear regression models were applied to the two gender specific strata with each of the body height adjusted parameters as dependent variable and age as predictor in order to calculate the predicted point estimates at the chosen common body height. Using the Microsoft Excel® (version 2016) function "Linest", the regression coefficients and all other statistics necessary for the estimation of predicted point estimates, confidence intervals and prediction intervals were calculated before back transforming all outcome measures to the individual body height of the person being tested. For further details on calculation of prediction intervals, see Harmon [14], Walpole et al. [15], or Vaugh [16]. Statistical procedures are illustrated in Fig. 1.

Similarly to confidence intervals and prediction intervals, percentile ranks can also be calculated. The percentile rank for a gait variable represents the percentage of persons with equal or lower values in the reference population. Two percentile points are commonly known; the 2.5 % and 97.5 %, which represent the 95 % prediction interval. The upper and lower bounds of the 95 % prediction interval represent the limits within which 95 % of measurements are predicted to be. Further the predicted point estimate represents the 50 % percentile rank.

The percentile rank for a specific measured value can be estimated by replacing the upper or lower bound of the prediction interval by the measured value, the choice of upper or lower bound depending on whether the measured value is above or below the predicted point estimate. The equivalent percentile rank can then be derived from the equation used to determine the prediction interval by calculating the t value representing the measured value adjusted to the chosen common body height. From the t value the equivalent percentile rank can be found since the underlying statistic has a t-distribution with n-2 degrees of freedom [15].

2.4. Back transforming height adjusted reference data to individual body height

When predicted point estimates with confidence intervals and prediction intervals for all spatiotemporal variables in the reference data base are calculated for a chosen common body height, all predicted values can be back transformed to any individual body height by the inverse of the procedures indicated by Eq.s 1–5 in order to compare measured individual gait data with reference data. The inverse procedure for Eq.s 1–3 is straight forward, while the inverse of Eq. 4–5 must take into account that the nominator and denominator require different procedures. It can be shown that predicted Velocity at a chosen common body height can be back transformed to the individual body height of person i (V_i) by inserting eq. 1 and 2 into eq. 4. Thus

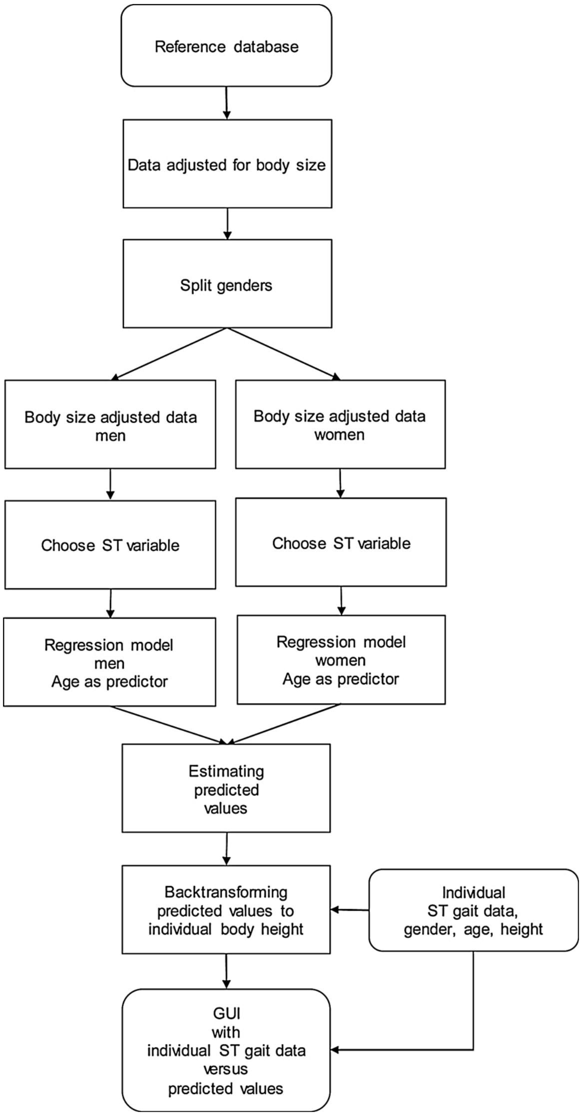


Fig. 1. Flowchart of statistical procedures. GUI: Graphical user interface. ST: Spatiotemporal.

$$V_i = SL_i/ST_i = V_{ai}\sqrt{(h_i/h_a)} \tag{6}$$

and Walk ratio adjusted to a chosen common body height back transformed for person i (WR_i) is found by inserting eq. 1 and 3 into eq. 5. Thus

$$WR_i = SL_i/(2*Cad_i) = WR_{ai}\sqrt{(h_i^3/h_a^3)} \qquad (7)$$

The percentile rank is a unitless figure and can be calculated directly from data adjusted to a chosen common body height.

2.5. The GUI calculator

Individually measured spatiotemporal gait scores can be entered into a GUI calculator developed in Microsoft Excel® 2016 which will display back transformed prediction point estimates updated with confidence intervals, prediction intervals and percentile ranks for all parameters entered (Fig. 2). Once the linear regression coefficients and other regression statistics representing the reference data base have been entered into the GUI calculator, the raw reference data are no longer needed for the GUI calculator to present reference data individualized that take gender, age, and body height into account.

3. Results

3.1. Method evaluation

Calculation of confidence intervals and prediction intervals done in the GUI environment with a Microsoft Excel® (version 2016) spreadsheet procedure were replicated in IBM SPSS® (version 24) with identical results. Calculations were further replicated for reference data adjusted to different common body heights with no change in the back transformed values.

Predicted probability (P-P) plots confirmed normality of the regression models, and plots of residual values against predicted values confirmed homoscedasticity. Test of multicollinearity was not relevant since regression analysis included one predictor only. Plots of age versus the spatiotemporal outcome variables confirmed a straight line relationship for the age ranges included.

Validity of the percentile rank procedure was confirmed in the GUI environment by calculating percentile ranks for all measured values equal to the upper and lower 95 % prediction interval bounds which resulted in percentile rank values of 97.5 % and 2.5 % respectively, and also for measured values equal to the predicted point estimates which resulted in percentile rank values of 50 %.

3.2. Validity of the reference data

In Table 2 our reference data are stratified by age to be compared to previously published reference data for older adults [3,9,17]. Unfortunately neither the same age strata ranges nor the same gait parameters were included in all studies. Therefore direct comparisons can not always be made, but Table 2 indicates that our reference data demonstrate somewhat higher mean preferred velocity and also a wider dispersion than the reference sources previously published. Number of subjects included differs vastly between studies.

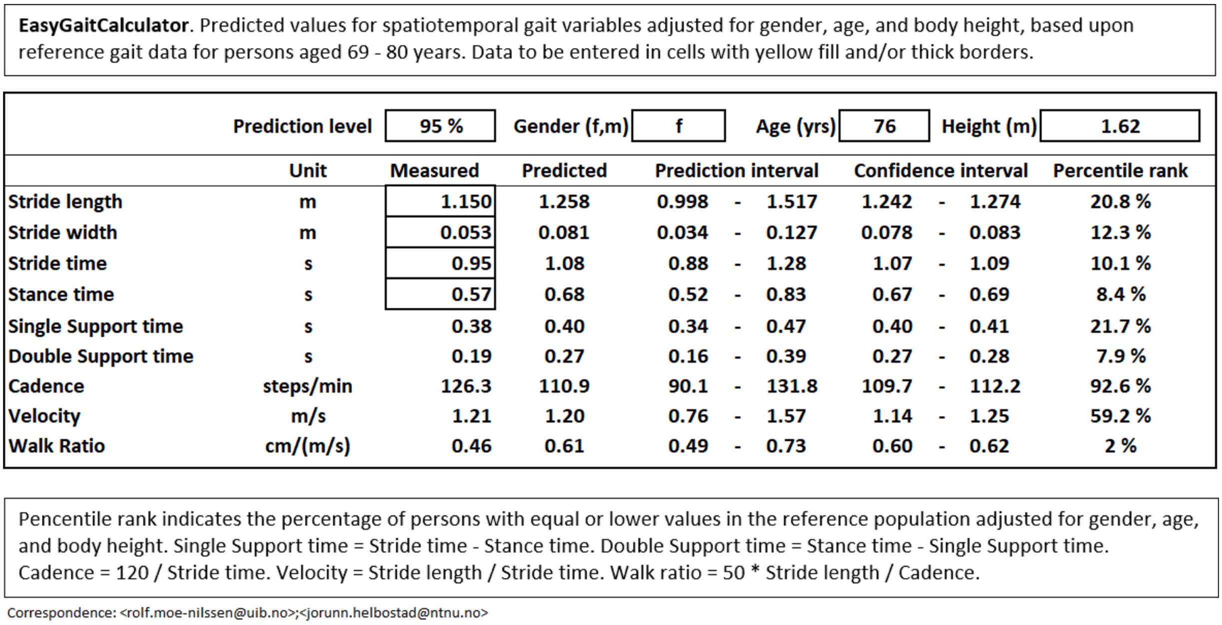
4. Discussion and conclusions

We have developed a spreadsheet-based solution based upon reference data for older persons with no impairments believed to affect gait where data are stratified by gender, and where body size is accounted for by intermediately adjusting data from the reference data base to a convenient common body height in accordance with physical laws [6,8]. This allowed height adjusted data for each gender to be entered into simple linear regression models with only age as predictor. The predicted reference values for each gait variable were finally back transformed to the body height of a single subject by a real time calculator using a reciprocal procedure. It was demonstrated that alternative choices of common body height did not affect the individualized end results after back transformation. All calculations were done using spreadsheet formulae and equations. The spreadsheet-based GUI called EasyGaitCalculator can be downloaded using a link to the free cloud storage service Dropbox (see Appendix 1) or by approaching the authors. Thus, the solution is available to clinical users.

Once the necessary regression coefficients and other statistics have been decided for each of the two gender strata, raw data are no longer needed in order to calculate prediction data. Therefore, the GUI can be used without direct access to the reference data base.

The percentile rank allows for direct comparisons between persons of different age and body height, and for comparisons over time for the same person. A higher percentile rank may be interpreted as a better performance for all parameters except for cadence where a lower percentile rank indicates a better performance.

The persons in the reference data base had an age range from 69 to



EasyGaitCalculator. Predicted values for spatiotemporal gait variables adjusted for gender, age, and body height, based upon reference gait data for persons aged 69 - 80 years. Data to be entered in cells with yellow fill and/or thick borders.

Prediction level 95 % **Gender (f,m)** f **Age (yrs)** 76 **Height (m)** 1.62

	Unit	Measured	Predicted	Prediction interval	Confidence interval	Percentile rank
Stride length	m	1.150	1.258	0.998 - 1.517	1.242 - 1.274	20.8 %
Stride width	m	0.053	0.081	0.034 - 0.127	0.078 - 0.083	12.3 %
Stride time	s	0.95	1.08	0.88 - 1.28	1.07 - 1.09	10.1 %
Stance time	s	0.57	0.68	0.52 - 0.83	0.67 - 0.69	8.4 %
Single Support time	s	0.38	0.40	0.34 - 0.47	0.40 - 0.41	21.7 %
Double Support time	s	0.19	0.27	0.16 - 0.39	0.27 - 0.28	7.9 %
Cadence	steps/min	126.3	110.9	90.1 - 131.8	109.7 - 112.2	92.6 %
Velocity	m/s	1.21	1.20	0.76 - 1.57	1.14 - 1.25	59.2 %
Walk Ratio	cm/(m/s)	0.46	0.61	0.49 - 0.73	0.60 - 0.62	2 %

Pencentile rank indicates the percentage of persons with equal or lower values in the reference population adjusted for gender, age, and body height. Single Support time = Stride time - Stance time. Double Support time = Stance time - Single Support time. Cadence = 120 / Stride time. Velocity = Stride length / Stride time. Walk ratio = 50 * Stride length / Cadence.

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Fig. 2. Screenshot of the The EasyGaitCalculator. Individual data to be entered in cells with thick borders, while cell contents in remaining cells will automatically be updated.

Table 2

Comparison of reference data from four different sources. Means and SD.

			Stride length		Stride time		Velocity	
		N	Mean	SD	Mean	SD	Mean	SD
Moe-Nilssen & Helbostad (2020)[1]	Men (70−79)	698	1.47	0.16	1.13	0.09	1.30	0.21
Beauchet et al. (2017)[2]	Men (65−84)	505	1.41	0.17	1.14	0.12	1.21	0.23
Hollman et al. (2011)[3]	Men (70−79)	57	1.38	0.13	1.16	0.08	1.20	0.15
Öberg et al. (1993)	Men (70−79)	14	1.23	0.07	1.05	0.10	1.18	0.15
Moe-Nilssen & Helbostad (2020)[1]	Women (70−79)	746	1.33	0.14	1.07	0.11	1.24	0.21
Beauchet et al. (2017)[2]	Women (65−84)	413	1.28	0.15	1.10	0.11	1.18	0.21
Hollman et al. (2011)[3]	Women (70−79)	110	1.20	0.16	1.06	0.13	1.14	0.19
Öberg et al. (1993)	Women (65−84)	15	1.08	0.05	0.99	0.10	1.11	0.13

[1] Stratified from raw data.

[2] Strata 65–74 and 75–84 years merged.

[3] Strata 70–74 and 75–79 years merged.

80 years, and had no impairments believed to affect gait. They were not screened for other diseases typically found in populations of older adults. Interpretation of results should take this into account.

Using these reference data for individuals younger than 69 years of age would require extrapolation and is not recommended. For persons older than 80 years of age straight line relationships between age and spatiotemporal gait variables are probably violated and more complex models than linear regression are required. Since the reference data are extracted from healthy persons believed not to have any gait impairments, data from persons with gait asymmetry or other impairments should be interpreted with caution. The reference population is mainly of Caucasian origin and the reference values may not be valid for populations representing other ethnicities. Also other anthropometric factors in addition to body height may differ between subjects and populations and affect validity of the chosen reference population.

The improved performance found in recent reference populations (see Table 2) may be caused by differences in inclusion criteria among studies, but may also be affected by improved functional capacity seen among elderly citizens in recent years [18].

All spatiotemporal parameters except Walk ratio are believed to be associated with velocity. The velocity association will add random error and thus camouflage important information unless controlled for. This can be done using more complex testing conditions like having subjects walk at a series of different instructions on speed (slow-normal-fast) [19]. Adding Walk ratio does not require such complex test setup, and may give valuable additional information about gait performance not found in previous reference data [20]. Walk ratio may easily be calculated when Stride length and Cadence are reported, which is almost always the case. Walk ratio is therefore strongly recommended to be included in a core set of gait variables. For between subjects comparisons, Walk ratios should be adjusted to a standardized body height (see eq. 1,3, and 5). An algorithm for comparing Walk ratios reported for different body heights is given in Appendix 2.

It should be noted that among the nine parameters included in the GUI, only Stride length, Stride width, Stride time, and Stance time were extracted from the reference data base and separately for each gender. It follows that only these four parameters need to be registered by a gait analysis procedure when asymmetry between left and right leg is not of interest, and gait variability is not an issue. The dependency between basic spatiotemporal gait parameters has not been highlighted in previous reports, but may facilitate testing and reporting and also minimize random error between parameters. Of the four registered parameters, Stride length and Stride time are possibly the parameters of highest clinical significance since Stance time is included in Stride time and was also proportional to Stride time (R = 0.97) in our reference data. More research is warranted to expand on this issue.

To the best of our knowledge, this is the first model presented for comparison of spatiotemporal gait parameters between individuals and a reference population of older adults where gender, age, and also body height are taken into account.

Similar GUI models can readily be applied for other reference populations where age can be assumed to be linearly related to spatiotemporal outcome variables. For curvilinear relationships, more complex models are needed.

Declaration of Competing Interest

None declared.

Acknowledgement

The gait assessment in the Generation 100 study was performed at the core facility NeXt Move, Norwegian University of Science and Technology (NTNU).

Appendix 1

Downloading the EasyGaitCalculator

The spreadsheet-based GUI called EasyGaitCalculator can be downloaded using this link to the free cloud storage service Dropbox:
https://www.dropbox.com/scl/fi/msb3r5fju8bcrsw61da7f/EasyGaitCalculator.xlsx?dl=0&rlkey=4f8gjr8rflqqxq8zcd7anmzc1

After the link has been activated, a preview of the GUI will appear. Choose Download > Direct download to save a copy of the EasyGaitComputor to your computer. Here individual gait data can be entered to be compared with reference population data adjusted for gender, age, and body height.

Appendix 2

The relation between Walk ratios normalized to different body heights

L = Step length
C = Cadence
h = body height
h_n = reference body height

L_n = Step length adjusted to a reference body height
C_n = Cadence adjusted to a reference body height
W = Walk ratio
W_{n1} = Walk ratio adjusted to body height 1
W_{n2} = Walk ratio adjusted to body height 2
X = the relation between two Walk ratios adjusted to different body heights

$$W = \frac{L}{C}$$

$$L_n = \frac{Lh_n}{h}$$

$$C_n = C\sqrt{\frac{h}{h_n}} = \frac{C\sqrt{h}}{\sqrt{h_n}}$$

$$W_{n1} = \frac{L_{n1}}{C_{n1}} = \frac{Lh_{n1}\sqrt{h_{n1}}}{hC\sqrt{h}}$$

$$W_{n1}X = W_{n2}$$

$$\frac{Lh_{n1}\sqrt{h_{n1}}}{hC\sqrt{h}}X = \frac{Lh_{n2}\sqrt{h_{n2}}}{hC\sqrt{h}}$$

$$X = \frac{h_{n2}\sqrt{h_{n2}}}{h_{n1}\sqrt{h_{n1}}} = \frac{\sqrt{h_{n2}^3}}{\sqrt{h_{n1}^3}}$$

$$Wn1\frac{\sqrt{h_{n2}^3}}{\sqrt{h_{n1}^3}} = Wn2$$

$$\frac{W_{n1}}{\sqrt{h_{n1}^3}} = \frac{W_{n2}}{\sqrt{h_{n2}^3}}$$

An example: In one study, mean Walk ratio (W_1) was found to be 0.62 after each individual body height had been adjusted to a reference body height of 1.67 m. In another study mean Walk ratio (W_2) was found to be 0.64 after each individual body height had been adjusted to a reference body height of 1. 73 m. Which of the two studies reported the highest Walk ratio? This can be estimated if mean Walk ratio of the first study (W_1) is adjusted to the reference body height used in the second study;

$$0.62\ \frac{\sqrt{1.73^3}}{\sqrt{1.67^3}} = 0.62\ \frac{2.275}{2.158} = 0.654$$

Conclusion: The Walk ratio of 0.62 in the first study was equivalent to a Walk ratio of 0.654 when normalized to the body height (1.73 m) of the second study. This is higher than the Walk ratio reported for the second study, which was 0.64.

The same procedure can be used to compare two unadjusted WRs between individuals of unequal height.

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