

Enhanced Gait Variability Index in Older Asian Adults and Increased Physiological Fall Risk: Results from the Yishun Study

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Abstract

Background: Gait variability (GV) of various spatiotemporal parameters has been investigated in association with falls as well as physical and cognitive decline. However, the lack of consensus regarding the best approach to quantify GV as well as the lack of a composite score to represent the variabilities of the various spatiotemporal gait parameters, had dampened the reporting and acceptance of GV, especially among Asian researchers. The main objective of this study was to derive an Enhanced Gait Variability Index (EGVI) and reference values in an Asian population and to evaluate its validity as an indicator of physiological fall risk.

Methods: This cross-sectional study was conducted in a large residential town of Yishun in Singapore. Random sample of community-dwelling adults (N = 511, 21 – 90 years old) categorized into 3 groups – reference group (N = 268, 21 – 64 years), low fall-risk (N = 182, \geq 65 years) and high fall-risk (N = 61, \geq 65 years). Physiological Profile Assessment (PPA) score of \geq 2.0 was used to differentiate high fall-risk and low fall-risk groups. EGVI were derived from 5 spatiotemporal parameters: step length(cm), step time(s), stance time(s), single support time(s) and stride velocity(cm/s), with reference values from among participation less than 65 years of age.

Results: Our Asian population showed greater overall gait variability than the European cohort in which the original EGVI was derived. This Asian EGVI displayed a non-linear relationship with both ageing and gait speed – significant changes in the EGVI were observed for those older than 60 years of age and in those whose habitual gait speed was lesser than 120cm/s. The EGVI discriminated between older adults with and without high fall risk and showed weak to moderate correlation with a number of the functional mobility and balance tests in both high and low fall risk groups.

Conclusion: We derived an Asian Enhanced Gait Variability Index and reference values and validated its performance to discriminate high fall-risk and low fall-risk among older adults.

Background

Gait variability (GV) refers to the change in spatiotemporal characteristics between steps. Sensitive to age-related mobility deficits and pathological processes, GV changes have been used to predict falls [1-3], cognitive decline [4] and dementia [5]. With the advancement in technology, it is now possible to quantify both macro and micro levels of gait changes without the use of expensive equipment. The use of wearable technologies such as smartwatches and accelerometers to monitor gait within the community-dwelling healthy population have further opened up opportunities to identify fall-risk [6] and cognitive impairment [7]. However, the use and reporting of GV have not gained wide acceptance due partly to the lack of consensus regarding the best approach to quantify them [8] as well as the lack of a composite score to represent the variabilities in the many spatiotemporal parameters of gait [9]. A composite measure for GV could enable comparison between populations, it also could allow clinicians to track GV changes in association with pathological processes.

As such, investigators have developed composite scoring indices for GV, e.g. Gillette Gait Index (GGI) [10] and the Gait Deviation Index (GDI) [11]. Gouelle et al. (2013) [9] developed and validated the Gait Variability Index (GVI) as an alternative to the GDI and the GGI. The GVI is a conglomerate measure of GV of nine spatiotemporal parameters [9]. More recently, Gouelle and colleagues further introduced the enhanced GVI (EGVI) with improved magnitude and directional specificity of the GVI by refining the calculation methods and removing four of the nine redundant / overlapping spatiotemporal parameters [12].

The work on GVI and EGVI have been limited to diseased populations [13,14], but there is potential for the use of this composite index as an indicator for mobility deficits, fall-risk and cognitive impairment in community-dwelling older adults. Furthermore, GVI/EGVI has not been studied in Asian populations, and is without Asian EGVI reference values.

Thus, the main objective of this study was to derive EGVI reference values in an Asian population and to evaluate its validity as an indicator of physiological fall risk.

Materials And Methods

Setting

Community-dwelling adults (≥ 21 years) were recruited from a large north-eastern residential town of Yishun in Singapore, with a residential population of 220,320 (50.6% females), with 12.2% older adults (≥ 65 years). This is similar to the overall Singapore residential population [15] of 4,026,210 (51.1% females), with 14.4% older adults (≥ 65 years).

Participants

Random sampling was employed to obtain a representative sample of approximately 300 male and 300 female participants, filling quotas of 20–40 participants in each sex- and age-group (10-year age-groups between 21–60; 5-year age-groups after 60). Older adults (above 75 years old) were also additionally recruited through community and senior activity centres. Participants were excluded if they had physical disabilities that limited their activities of daily living; diagnosed with either cognitive impairment or any neuromuscular disorders; or suffering from more than five poorly controlled co-morbidities or chronic illness. Ethics approval was obtained from the National Healthcare Group Domain Specific Review Board (DSRB – 2017/00212) and written consent was obtained from all participants.

Methods

A 6 m instrumented walkway system, GAITRite® (CIR systems, USA, 120 Hz sampling rate) was used for the gait analysis. Participants were instructed to initiate their gait 1 m before and end 1 m after the

walkway system, to account for any gait related accelerations or decelerations, respectively. Participants were instructed to walk barefoot at their self-selected (habitual) gait speed. After a practice trial, three valid trials were recorded. A trial was considered valid if at least 6 alternate footfalls were captured within the sensor platform. Spatiotemporal parameters [Fig. 1] were automatically calculated by the walkway software (Version 4.8.5). Gait speed was estimated from the mean stride velocity of the participants.

Prior to the gait assessments, participants performed two common functional mobility tests- the Timed-up and Go (TUG) [16] and the Five Times Sit to Stand Test (5XSTS). Participants performed the TUG twice and the mean value was used for analysis. As for the 5XSTS, participants were provided a single practice trial, after which the actual test was performed. Additionally, they also performed the short-Physiological Profile Assessment [17]. The short-PPA has been validated as an indicator of fall risk in older adults [17–19]. It consists of five sub-tests: (a) Melbourne Edge Test (b) hand reaction test (c) proprioception (d) knee extension strength (e) postural sway. However, only the last 3 sub-tests, which are related to the lower limb, are discussed in this study.

Participants aged 65 and above and with a fall risk score of 2.0 and above were categorized as the “High Risk” (HR) group and the rest as “Low Risk” (LR) group [17]. Those below the age of 65 were classified as the “Healthy Control” (HC) group and were included in the computation of the reference population’s EGVI.

EGVI Calculation

Alternative parameters [9], p_n , which describes the intra-trial variability of step time (s), step length (cm), stance time (s), single support time (s), stride velocity (cm/s) from data of all subjects ($n = 531$) were included in the Principal Component Analysis (PCA) to compute the correlation coefficient, c_n , that describes the contribution of each variable to the overall variability of the data. For the computation of alternative parameters, a macro [an Excel version was provided as a supplementary material by Gouelle et al. (2013)[9]] was implemented in R Studio (Version 3.6.1). The results of the PCA analysis suggested that close to 50% of the variance was explained by the first principle factor alone [Fig. 1]. However, this was substantially lower than those reported by Gouelle et al. (2013)[9]. Stride velocity and stance time contributed most to the overall gait variability, with all of the variables achieving correlation of at least 0.6 with the principle component [Fig. 1]. These coefficients were used as weights in the EGVI calculation as explained below.

The EGVI was calculated using a modified macro [an Excel version was also provided as a supplementary material by Gouelle et al. (2013)[9]] that was again implemented in R Studio (Version 3.6.1). Modifications were based on Gouelle et al. (2018) [12], and they primarily pertained to addressing issues related to (a) magnitude (b) direction (c) and redundancy. The details of the calculation and modifications are presented elsewhere [9, 12]. Here, we only highlight the key steps involved in the derivation of the EGVI.

First, the mean sum of product, s^{HP} , was calculated based on the 5 spatiotemporal parameters [see above] of 215 healthy participants [aged 21 to 65 and gait speed ≥ 100.0 cm/s] by matrix multiplication (see Gouelle et al., 2013 [9] for more details) of the weighted coefficient, c_n , and the alternative parameters, p_n . The s^{HP} for this group was 18.05, which was close to Gouelle et al. 2013 [9]. Then, the sum of product of each participant, s^a , was computed [again by matrix multiplication] and the absolute distance, $d^{a,HP}$, between this participant (s^a) and the healthy control group (s^{HP}) was calculated. An addition of 1 was added to $d^{a,HP}$ prior converting this value to the raw EGVI ($EGVI_{raw}^a$). If the sum of product of this participant, s^a , was lower than the control group ($s^{HP} = 18.05$), the $EGVI_{raw}^a$ was negated. If it was in the range of the mean raw EGVI of the healthy control group $[-EGVI_{raw}^{HP}, +EGVI_{raw}^{HP}]$, then a value of $EGVI^a = 100$ was assigned to this participant, otherwise the z-score was computed, thereafter multiplied by 10 and add to a 100. This would be the participant's EGVI. An EGVI score of 100 indicated that the participant's gait variability was close to the healthy/control population and any deviations from the 100, more indicating greater and less indicating lower gait variability compared with the reference group [9, 12].

Statistical analysis

Mann–Whitney U non-parametric test was used to evaluate differences in raw EGVI, EGVI between populations. Student's t-test was used to evaluate differences in all other continuous variables, including participant characteristics. Stepwise linear regression models for fall risk were built to examine the independent as well as combined effects of EGVI and gait speed. Linear modelling investigated the relationship between (a)EGVI and Age; (b)EGVI and gait speed. Whenever the scatterplots suggested possible quadratic relationship, the models were tested for significant improvement in adding a quadratic term to the model. Discriminatory power of EGVI was explored using ROC analysis. Pearson correlation was used to assess the relationship between EGVI and functional mobility and balance assessments. Significance level (α) was set to 0.05 for all statistical tests. Statistical analysis was performed in R Studio (Version 3.6.1).

Results

Table 1 shows the profile of the participants grouped according to age and PPA fall risk. Twenty participants who did not complete all 3 of the PPA subtasks were excluded from further data analysis. Complete gait data was available in 511 subjects. The HR group was significantly older than the LR group. They were also significantly shorter, although there were no differences in their weight and BMI. As for their fall risk score (PPA), there was a significant difference between the two groups – the mean PPA score of the HR falling within the “Marked” range, whereas the LR falling within the “Normal” range. The HR group also walked significantly slower than the LR group. The HR group had a significantly greater EGVI compared to the LR group.

Table 1
Profile of participants (Mean & Standard Deviations)

	Healthy Control (HC) (n = 268)	Low Risk (LR) (n = 182)	High Risk (HR) (n = 61)
Age*	43.82 ± 13.80	73.52 ± 5.56	79.78 ± 5.70
Gender (% female)	57.5%	55.5%	59.0%
Height (cm) [†]	162.72 ± 8.49	157.66 ± 7.86	154.53 ± 8.53
Weight (kg)	67.85 ± 16.41	60.13 ± 9.46	58.06 ± 11.26
BMI (kg/m ²)	25.53 ± 5.33	24.17 ± 3.20	24.30 ± 4.19
PPA [‡]	-0.05 ± 0.81	0.76 ± 0.72	2.86 ± 0.75
Gait speed (cm/s) [§]	113.48 ± 16.32	100.53 ± 17.55	84.26 ± 18.96
EGVI	101.10 ± 6.70	105.03 ± 9.18	113.61 ± 10.72
* HR group were significantly older than the LR group			
† HR group were significantly shorter than the LR group			
‡ HR group were significantly at greater fall risk than the LR group			
§ HR group walked significantly slower than the LR group			
EGVI for HR group was significantly greater than the LR group			

The Asian EGVI

The raw EGVI of the local reference population (1.28 ± 0.64) was significantly lower ($p < 0.001$) than those reported by Gouelle et al. (2013) (1.39 ± 0.62) [recomputed after implementing the modification recommended in Gouelle et al. (2018)[12]].

Relationship between EGVI with age and gait speed.

Figure 2(a) shows the change in EGVI with age. There appears to be no gradient till around the 60 s, after which a steady increase in EGVI is observed. The EGVI for those above 65 and above [107.18 ± 10.27] was significantly greater ($p < 0.001$) than those below 65 [101.10 ± 6.70]. Figure 2(b) shows the relationship between gait speed and EGVI: those who walked with a slower self-selected gait speed had increased gait variability compared to the healthy control group, with EGVI appearing to be constant at gait speeds > 120 cm/s.

EGVI ability to discriminate fall risk groups in older adults

The EGVI of the HR group (113.61 ± 10.72) was significantly greater ($p < 0.001$) than the LR group (105.03 ± 9.18). Linear regression models for fall-risk (dependent variable – PPA score) for both EGVI and gait speed suggested that both variables make independent contribution to fall risk, but the addition of EGVI significantly improved ($p = 0.0143$) the model with gait speed alone [Table 2]. When we further investigated the alternative parameters, only $p_{step_length_mean}$ maintained significance after controlling for age, gender, height and gait speed. The discriminatory power of the EGVI as well as gait speed were similar and within acceptable range, with AUC = 0.807 [95% CI – 0.741, 0.873] and AUC = 0.805 [95% CI – 0.739, 0.871], respectively. Combining EGVI with gait speed did not significantly improve ($p = 0.621$) the discriminatory power.

Table 2
Linear regression models for fall-risk (Dependent variable – PPA scores)

	B	SE (B)	β	<i>p</i>	<i>Adj. R</i>²
Controlling for Age, Gender and Height					
Independent variable					
EGVI*	0.029	0.007	0.297	< 0.001	0.332
Gait Speed *	-0.014	0.004	-0.275	< 0.001	0.321
$p_{step_length_mean}^*$	0.268	0.046	0.396	< 0.001	0.369
$p_{step_time_mean}$	0.167	0.062	0.181	0.008	0.300
$p_{stance_time_mean}$	0.186	0.064	0.195	0.004	0.303
$p_{single_support_time_mean}^*$	0.130	0.037	0.232	< 0.001	0.315
$p_{stride_velocity_mean}^*$	0.192	0.056	0.228	< 0.001	0.313
Controlling for Age, Gender, Height and Gait Speed					
EGVI*	0.021	0.008	0.213	0.014	0.336
$p_{step_length_mean}^*$	0.240	0.055	0.354	< 0.001	0.369
$p_{step_time_mean}$	0.072	0.069	0.078	0.299	0.322
$p_{stance_time_mean}$	0.085	0.073	0.297	0.250	0.322
$p_{single_support_time_mean}$	0.076	0.044	0.134	0.084	0.327
$p_{stride_velocity_mean}$	0.115	0.063	0.137	0.069	0.328
* significant at $\alpha = 0.05$					

Relationship between EGVI, functional mobility and balance assessments

The EGVI for both the HR and LR groups were moderately and positively correlated with the tests of functional mobility – TUG and 5XSS. The overall fall risk PPA score was also weakly correlated with EGVI, although more strongly for the HR group. The KES was negatively correlated with EGVI for both groups [Table 3].

Table 3
Correlational (Pearson) relationship between EGVI and function mobility and selected fall risk assessments

	Low Risk (n = 182)	High Risk (n = 61)
PPA [†]	0.230*	0.350*
Proprioception	- 0.001	0.108
KES [‡]	- 0.260*	- 0.337*
Sway [§]	0.094	0.087
TUG	0.554*	0.679*
5XSS [¶]	0.337*	0.462*
*: significances at p < 0.01		
†: PPA – Physiological Profile Assessment		
‡: KES – Knee Extension Strength		
§: Sway – PPA : Foam eyes open component of PPA		
: TUG – Timed-up and Go assessment		
¶: 5XSS – 5 times sit-to-stand		

Discussion

This study derived and described Asian EGVI reference values and investigated its validity as an indicator for fall risk among older adults. Our results showed that this Asian healthy population had greater overall gait variability compared with the European cohort. The EGVI of our population did not have a linear relationship with age and habitual gait speed. The EGVI was almost constant till the 60's, after which it started to increase steadily. Furthermore, people with slower habitual gait speed had a greater EGVI or overall gait variability. The PPA provides valid and reliable measurements for assessing falls risk and

evaluating the effectiveness of interventions [17]. We also demonstrated the validity of EGVI to discriminate between older adults with and without high PPA fall risk. Interestingly, only a single alternative parameter – $p_{step_length_mean}$ – was significantly associated with fall risk score. The EGVI had weak to moderate correlation with a number of other functional mobility and balance tests (including TUG, another fall risk assessment) [16] in both high and low fall risk groups, further substantiating its validity as a composite index for GV in our older Asian population.

Our control participants elicited significantly greater values in six [mean step length, mean step time, mean single support time, mean stride velocity, SD step length and SD stride velocity] out of the 10 alternative parameters [see Fig. 1], p_n , used in the calculation of intra-trial gait variability – thus suggesting greater overall GV compared to a Western population. Differences in gait parameters between Asian and the Western populations have been reported [20] but with no definitive conclusion on difference in GV. Differences were reported mainly in stride length and walking speed and was attributed to the smaller stature of the Asian subjects [20], but these physical differences were unlikely to have any effect on GV. It is plausible that the differences in our study could have been due to the different age range or the percentage of females included in the control populations since both age [21, 22] and gender [23] have been associated with gait variability.

The EGVI of our population was affected by age as well as gait speed. Balasubramanian et al. (2015) [24] reported that the GVI decreased with advancing age but showed no relationship in those who were younger than 50. This was not surprising since variability in most of the gait spatiotemporal parameters increases with age [21], especially among older adults [22–25]. Furthermore, the slower the self-selected gait speed of the older adults, the greater was their EGVI. This again was not surprising since gait variability increases as the walking speed decreases [26]. However, the increase in the EGVI among those who were greater than 60 years old were likely due to age-related muscle weakness and loss of flexibility, rather than solely due to the reduction in gait speed [27, 28].

Balasubramanian et al. (2015) [24] validated the use of the GVI to discriminate high-functioning older adults from those with mild to moderate mobility deficits. Schmitt et al. (2020) [14], validated the use of the composite EGVI versus individual spatiotemporal parameters among the PD population to assess for fall frequency. Others, such as Kalsi-Ryan et al. (2020) [13], has validated the EGVI to discriminate patients of varying severities of Degenerative Cervical Myelopathy (DCM). Our study is the first to report the validity of EGVI to discriminate older, healthy community-dwelling adults who were at higher physiological fall risk. EGVI in our population successfully distinguished those who fell within the “Marked” fall risk range from those in the “Normal” range. An increase in fall risk has been closely linked to the increase in gait variability among older adults in community dwelling [2, 29], although which spatiotemporal parameter was most sensitive to capture this fall risk is still debatable. However in this study, we found that increased $p_{step_time_mean}$ was associated with physiological fall risk. Although the alternative parameters, p_n , could not be directly compared with published values of gait variability [due to methodological differences in derivation], our results suggested that the increase in variability of step

length - which has been associated with falls, specifically in populations with cognitive deficits [30] – may indicate the strong association between cognitive demands and falls, especially among older adults.

The EGVI is a convenient yet sensitive composite score to quantify these various spatiotemporal changes in relation to fall. Furthermore, we also showed that the EGVI was significantly correlated with common functional mobility and balance assessments. This was contrary to Balasubramanian et al. (2015) [24], who reported moderate to strong but non-significant correlations between the GVI and various clinical measures of mobility and balance. Our larger sample have likely allowed us to better explore the relationships.

Study Limitations

The strengths of this study are its population-based nature and thoroughness of data collection. This study also has limitations. Firstly, while we used a well validated physiological fall risk assessment and other functional mobility tests, we did not investigate actual falls. We were also not able to validate the local EGVI with a more varied or diseased population as this was part of a normative study of a generally healthy population.

Future Recommendations

The strength of the EGVI as a composite score should not be limited to a fall-risk indicator as gait speed alone could be useful for that. In addition to physiological changes, EGVI may also be associated with cognitive changes. Thus, we recommend that future studies should investigate not only the validity of our Asian EGVI reference with a population which has more serious functional mobility issues but also those with cognitive impairment. There has been active research in the areas of cognition and gait variability, and the EGVI might provide a meaningful composite score that could be easily referenced within the clinical community interested in cognitive decline.

Conclusions

We presented and discussed EGVI reference values for an Asian population. We also validated this reference with an older population with a higher fall risk and established the validity of EGVI as a composite GV index in an older population. Our Asian EGVI reference values should be further validated in and applied to various clinical populations with gait limitations and higher risk of falls, for example those with stroke, dementia and Parkinson disease etc.

Abbreviations

5XSTS: Five Times Sit to Stand Test

EGVI: Enhanced Gait Variability Index

GV: Gait Variability

GVI: Gait Variability Index

HC: Healthy Control

HR: High Fall Risk group

KES: Knee Extension Strength

LR: Low Fall Risk group

PCA: Principal Component Analysis

PPA: Physiological Profile Assessment

TUG: Timed-up and Go Test

Declarations

Ethics approval and consent to participate

Written informed consent was obtained from the participants for the research and the publication of its results. All procedures were approved by National Healthcare Group Domain Specific Review Board (DSRB – 2017/00212).

Consent for publication

Consent for publication has been obtained from all authors listed as well as those acknowledged in this study.

Availability of data and materials

The datasets used and analyzed in this current study are available from the corresponding author on reasonable request and with permission of Geriatric Education and Research Institute (GERI), Singapore.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

KAJ: Conceptualization, Methodology, Formal Analysis, Investigation, Resources, Data Curation, Writing – Original Draft, Writing – Review & Editing, Project Administration. WTS: Conceptualization, Methodology, Writing – Review & Editing, Project Administration. LKL: Formal Analysis, Investigation, Resources, Data Curation, Project Administration BWP: Formal Analysis, Investigation, Resources, Data Curation. DHMN: Formal Analysis, Investigation, Resources, Data Curation. QLLT: Formal Analysis, Investigation, Resources, Data Curation. KKC: Formal Analysis, Investigation, Resources, Data Curation. MUJ: Conceptualization, Methodology, Supervision. TPN: Conceptualization, Methodology, Supervision. SLW: Conceptualization, Methodology, Supervision, Funding Acquisition.

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Figures

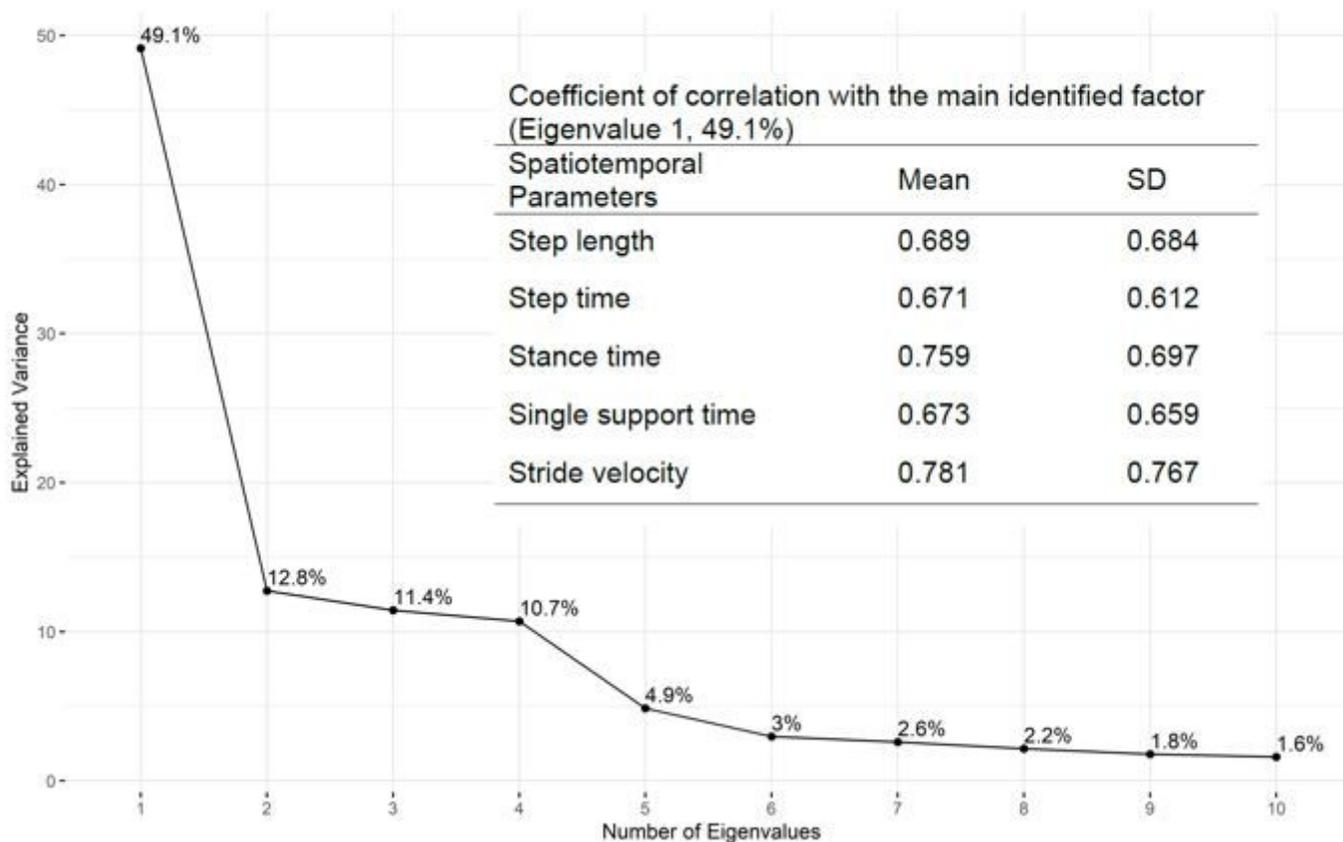
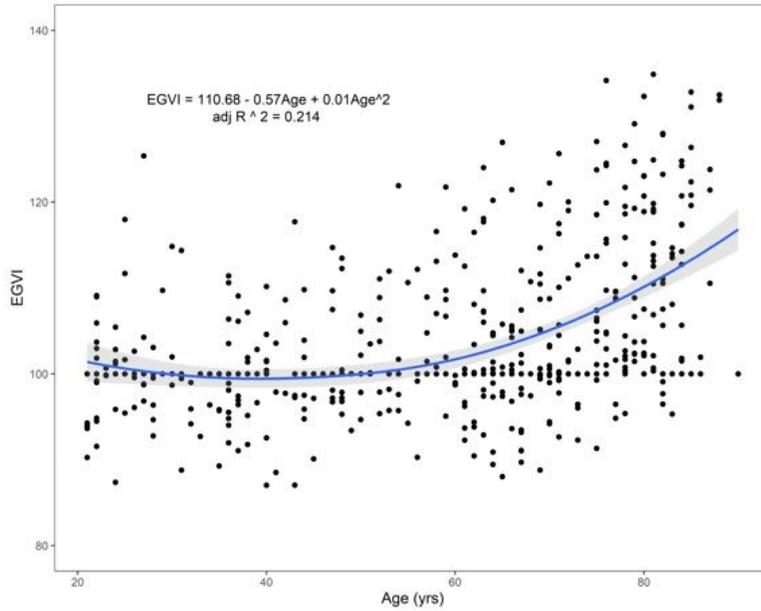


Figure 1

Results for Principal Component Analysis: Eigenvalues and their respective explained variance

(a)



(b)

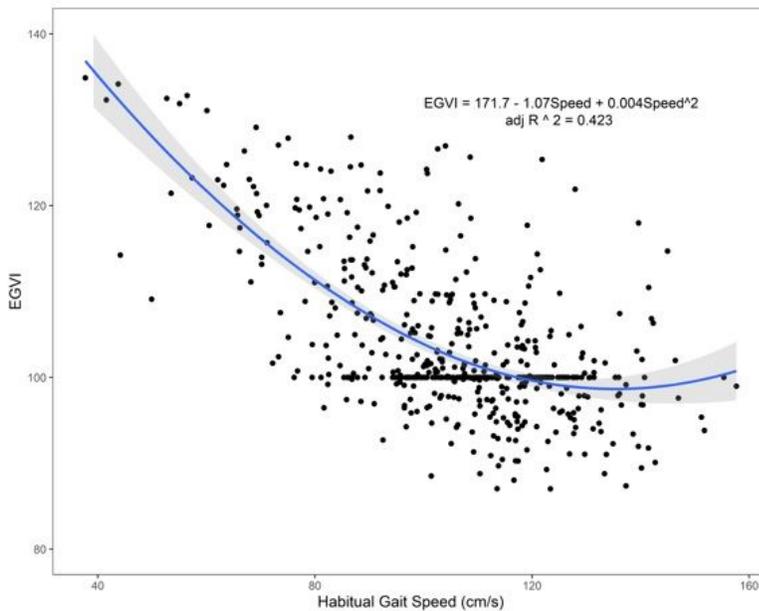


Figure 2

(a) Relationship between Enhanced Gait Variability Index and age (n = 511). There is no relationship between EGVI and age before approximately 60 years of age, after which we observe a steady increase in EGVI with advancing age. (b) Relationship between Enhanced Gait Variability Index and habitual gait speed (n = 511). EGVI decreased steadily with increasing habitual gait speed but not so after 120cm/s.