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Age is just a number: Clustering gait and functional measures

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ABSTRACT

Objective: As we age, we walk slower, but it remains unclear whether this is consistent at an individual level. Current clinical assessment of function assumes movement deficits with older age, and clinical norms are linked to decades or specific age stratifications such as "old" or "oldest-old". Current approaches stratifying by age may hide trends of higher and lower functioning individuals within each age bracket. Therefore, our aim was to cluster spatiotemporal data, from the 1000 Norms Project, to understand if patterns of function could be identified without using age as a factor.

Methods: The 1000 Norms Project, a cross-sectional, observational study, collected gait, functional performance, and self-reported health data (participants (n = 695) aged 18–92 years). Spatiotemporal and functional data were clustered, after rendering the parameters dimensionless.

Results: Three clusters were identified (n = 277, 208, 210). Although age significantly differed between clusters, each showed a broad range (e.g. 20–92 years). Additionally, walking speed (Froude number) did not differ between clusters, often used to separate by age. Our clusters defined 3 groups, 'higher functioning', 'age average' and 'cautious gait', whose spatiotemporal, functional performance, strength and quality of life measures vastly differed, independent of walking speed and including a wide range of ages.

Conclusion: Our analysis suggests that age should not be used to separate individuals into groups, and that our assumption of "age matters" may not be relevant when determining true functional movement ability. Further work is needed to understand normal senescence, true negative loss, and reversible loss within these functionally different groups.

1. Introduction

Advancing age is accompanied by changes to strength, balance, and fitness which contribute to declines in mobility, function, and walking. Older adults therefore employ a more cautious gait [1] reducing walking speed, cadence and step length. Changes in spatiotemporal parameters impact joint biomechanics with a recent review [1] in younger and older adults showing significant moderate-to-large, standardised effects of age for ground reaction forces, ankle kinematics, moments and powers. Generally, studies investigating biomechanical changes with age [1,2] compare young to older adults. But walking speed declines within a decade [3] and with age [4]. Therefore, having one group of older adults as a comparator may not be appropriate and could hide decade-specific changes in function.

The 1000 Norms Project is a cross-sectional observational study investigating outcome measures of walking spatiotemporal parameters, physical function, and self-reported health in 1000 healthy individuals aged 3–101 years [5]. Previous 1000 Norms Project work [6] showed that walking speed was stable during adolescence (10–19 years) and adulthood (20–59 years), while children (3–9 years) and older adults (>60 years) walked at comparably slower speeds. Similarly, across the literature, walking speed has only been compared across relatively broad adult age groups. For example, walking speed for > 50 years declines by approximately 0.1 m/s per decade [7], and this speed reduction increases to 26 % slower for ≥ 90-year-olds compared to 80–89 years [8]. Walking speed is therefore key to functional decline with age.

Cohen-Mansfield [9] defined 'old' as 75–84 years, 'old-old' as 85–94 years, and 'oldest-old' as > 95 years. This categorisation of age showed declines in Activities of Daily Living (ADL), Instrumental Activities of

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Daily Living (IADL), cognitive function, and physical activity across age. Therefore, older adults should not be grouped as a single category, as function clearly continues to decline with age. A recent review emphasises that “older adult” is not a single category as there is little consensus on a) the age stratifications used to define the “oldest old” which ranged from > 75 to > 92 years and b) the terminology used to describe these stratifications [10]. Instead, Kydd et al. [10] recommended that older adults should be grouped by decade. We lack clear understanding of how gait and function change with age but stratifying by age could be adding to the confusion. Therefore, we need to analyse gait and function across age to understand what normal senescence is and what is true negative loss.

One alternative approach is to cluster participants by gait measure(s) rather than stratify by age. An unsupervised machine learning technique (clustering) identifies basic patterns and relationships in datasets. Clustering is not predetermined by arbitrary classification i.e. younger vs. older, but based purely on the data [11]. A clustering approach is widely used to classify gait patterns among patients (e.g. cerebral palsy [12], diabetes [13], arthritis [14], chronic stroke [15], amputation [11] and in healthy individuals [16,17]. Watelain et al., [16] used a clustering approach to distinguish between young (n = 16) and older participants (n = 16) using only biomechanics. Joint kinetics differed between young and older participants, with the older participant group separating into 3 distinctive cluster ‘families’. Similarly, Liang et al. [17] clustered older adults (n = 8; 64(6) years) and younger adults (n = 12; age 29(5) years) finding that ankle moment, knee angle, hip flexion angle and hip adduction moment were non-age-related features, suggesting that these were ‘essential indicators for gait with normal function’. Both these studies support the notion that older adults cannot be grouped into a single homogenous group.

Scaling may be an additional confounder within biomechanical data that could impact differences between older and younger groups. Length (i.e. height, leg length) and mass are key factors that impact biomechanical outcomes [18]. For example, individuals with a mass of 60 kg, will have a lower ground reaction force than an individual of 80 kg due to body support requirements. Scaling is reflected in joint kinetics as the absolute value of generated internal joint moments would differ. Therefore, normalising purely by body mass [16] is not sufficient to account for both the length (moment arm) and mass effects associated with moments (Nm). Data should be “normalised”, or made dimensionless, to ensure all anatomical aspects that are impacted by scale are accounted for within the outcome [19].

We therefore propose to use a clustering approach on “normalised” spatiotemporal and functional performance data, from the 1000 Norms project, to determine whether patterns of function can be determined based on an individuals’ gait data. Age therefore was not used as an explanatory variable as we have previously done [6]. Beyond the clustering we would identify if patterns were determined by function or whether age remained a factor. Moving away from the assumption of “age matters” may enable a more accurate assessment of gait and provide more appropriate clinical decision making to ensure individuals’ receive the needed interventions no matter what age they are.

2. Materials and methods

2.1. Protocol

These data were collected between January 2014 and September 2015 as part of the 1000 Norms Project [5,6] following institutional ethics approval (#2013/640). The overarching aim of the project was a cross-sectional observational study investigating gait, physical capability, and self-reported health in 1000 healthy individuals aged 3–101 years. For this current study, only participants aged ≥ 18 years were included. The population was recruited from individuals living in the Greater Sydney metropolitan (Australia). Participants were eligible if they were healthy by self-report and able to participate in age-appropriate activities. Individuals were excluded if they had health conditions affecting physical performance such as demyelinating, inflammatory, and degenerative neurologic conditions; diabetes mellitus; malignant cancers, pregnancy, body mass index ≥ 40, severe cardiac or pulmonary disease affecting daily activities; infectious or inflammatory arthropathies; history of major surgery affecting physical performance; severe mobility impairment leading to dependence on mobility aids for walking. For further details see the protocol paper [5].

2.2. Procedure

A brief overview is provided here for each measurement [5,6,20,21] used in this paper, but for further details please see the supplemental materials.

Spatiotemporal walking gait measures: The procedure for capturing the walking gait data has been described before as part of the 1000 Norms Project [6]. In brief, participants completed five walks at their comfortable pace, with a 2.5 m rolling start, across a Zeno™ walkway (1.8 ×3.9 m) (Protokinetics, Havertown, PA, USA) embedded with sensors sampling at 120 Hz. This study used, walking speed, step length, stride width, stance time, swing time, and total double support (definitions in Table S1).

Functional measures: The Six-Minute Walk Test (6MWT), Timed-up-and-down stairs (TUDS), 30-second chairs stand, and choice stepping reaction time test have been described previously as part of the 1000 Norms Project [20].

Strength measures: Hand grip, ankle dorsiflexors and plantarflexors were assessed via maximal voluntary isometric contraction using a hand-held dynamometer (Citec dynamometer CT 3001; CIT Technics, Groningen, Netherlands). The strength of knee flexors and extensors was assessed by fixed dynamometry (CSMi; HUMAC NORM, Stoughton, MA). These have been described previously as part of the 1000 Norms Project [22].

Psychosocial characteristics: These have been described previously as part of the 1000 Norms Project [20,21], briefly; all participants completed the AQoL-8D [23], a 35-item questionnaire, assessing eight dimensions and generates two super-dimensions (mental and physical) as well as a global “utility” score.

IPAQ: These have been described previously as part of the 1000 Norms project [20]. The International Physical Activity Questionnaire (IPAQ) long [24] 18–69 years or IPAQ elderly [25] (>70 years) was used. Total physical activity in the past week was calculated in MET-minutes.

2.3. Data and statistical analysis

In total n = 700 participants were included. We removed two participants; one who was 101 years old (no other participants in this age decade) and one from the 20–29 age group for having a walking speed < 1.0 m/s. This participant was an outlier as those who walked < 1 m/s were on average 77.1 (10.7) years old.

2.4. Normalisation

To ensure all anthropometric effects of length and mass were not confounding the outcome data, all relevant parameters were rendered dimensionless [19,26] (see Table S2). Velocity was converted to Froude number. This is a standardised method of normalising velocity based on a pendula motion impacted on by gravity. Therefore dynamic similarity of movement can only occur at equal Froude numbers [27,28].

2.5. Accounting for differences in Froude number in the data

To alleviate the issue of velocity impacting outcome data where the Froude number ranged from 9 % to 211 % of the average value, we regressed all outcome measures against velocity. If the regression was significant ($p < 0.05$) and our explained data (r^2) was biologically relevant (>0.15), then the residuals of the regression were used for further analysis [29]. Using the residuals removes the impact of velocity on the spatiotemporal parameters. Velocity significantly impacted 6MWT, Timed-up-and-down-stairs, stance time, step time, total double support time and step length. Therefore, from hereon in these outcomes were used as residuals from the regression. To ensure values were biologically relevant, the residuals were added to the average value for that outcome measure.

2.6. Clustering procedure

The initial steps which were taken i.e. unsupervised K-means clustering and the first PCA approach, which resulted in the final cluster model selection, are reported in the supplemental materials.

All statistical analyses were carried out using JASP (v 0.19.1) software. Initially an unsupervised K-means nearest neighbour clustering analysis optimised to BIC was performed. This resulted in 17-clusters which was deemed an unpractical option nor feasibly relevant [30] (Table S4). Therefore, a principal component analysis (PCA) approach was used to determine the number of components and which outcome measures were used to inform the number of clusters (i.e. a supervised method). PCA with oblique promax rotations was performed on 8 variables to derive independent summarising factors. These were a) spatiotemporal gait measures (Froude number, step length, stance time, double support time, swing time), and b) functional measures (6MWT, chair stand, TUDS). Factors were selected from the PCA if their eigenvalue was ≥ 1, signifying that each factor explains at least as much variance as a single variable. Communalities were calculated, reflecting the amount of variance in the variable explained by all factors. Variables were appointed to a certain factor if their correlation with the factor was ≥ 0.5 i.e. [31].

Three participants were missing either TUDS and/or 6MWT, so these were not included in further analysis resulting in 695 participants. Eight variables were included in the PCA (Table S3) yielding 3 oblique components and accounting for 77 % of variance. No further principal components were used as their eigen values were < 1. Component 1 accounted for 31 % of total variance, component 2 was 28 %, and component 3 was 17 %. A threshold for relevant item loadings was set at > 0.50 (Table S3).

The K-means Neighbourhood-based clustering was carried out using the 8 variables from the PCA. The training parameters were set to 3 fixed clusters, derived from the PCA components. For comparison, we also tested 2- and 4-cluster models (Table S4). The variables were scaled, the algorithm settings were means centred, Hartigan-Wong algorithm was applied, and a seed was set. Cross-validation of the 3- and 4-cluster models was performed by holding a random subset of the spatiotemporal and functional data, containing 10 % of the initial data and training and validation data using 10-folds [14].

The performance of the cluster models was assessed using BIC and AIC, silhouette, entropy, the Dunn index, and the Calinski-Harabasz index. The accuracy of the 3- and 4-cluster models was assessed via, percentage number of participants misclassified, and the validation of the model was assessed via F1, Matthews Correlation Coefficient, and Recall metrics.

To validate the cluster solution, we determined to what extent the derived clusters could distinguish between domains of function, strength, quality-of-life, physical activity and spatiotemporal parameters. This analysis comprised a between cluster comparison of each domain to examine if the number of clusters derived ($n = 3$) resulted in distinctive groups. A one-way ANOVA was used to compare clusters for each domain. If statistically significant a post-hoc Bonferroni corrected analysis was performed. Significance was set at $p < 0.05$. A sensitivity analysis (one-way ANOVA and Chi-square tests were used for nominal data) comprised a between-cluster comparison of participant demographics (age, mass, height, and sex). ω^2 was calculated to represent effect size with 0.010 indicating a small effect, 0.059 a moderate effect and 0.138 a large effect [32] respectively. ω^2 was chosen as it is less biased than other strength of association measures which tend to overestimate the population's effect size [33].

3. Results

The descriptive data (Table 1) are presented for the whole data set as well for each decade, except for the 80–92-year-old group which included 4 participants who were ≥ 90 years.

3.1. K-means nearest neighbour clustering

The supplemental materials presents the results for the unsupervised model ($n = 17$ clusters) as briefly described in the methods.

The 3 components identified via the PCA were used to inform the number of clusters for the K-means clustering. This partitioned the 695 participants into three-clusters of $n = 277$ for cluster 1, $n = 208$ for cluster 2, and $n = 210$ for cluster 3. The AIC and BIC were 3853.9 and 3962.9 respectively with an R^2 of 0.314 and a silhouette of 0.180. This was also compared to two- and four-cluster model (Table S4). Compared to the three-cluster model, the two-cluster model had notably higher BIC and AIC, whilst the four-cluster model had lower BIC and AIC (Table S4). The accuracy of the 3- and 4-cluster model (i.e. ability to classify participants into the appropriate cluster) was 94.2 %. Despite both models reporting similar average accuracy, the 3-cluster model outperformed the 4-cluster model in terms of F1, Matthews Correlation, and recall (Table S4). These performance measures were also markedly reduced (0.4, 0.489. and 0.25 respectively) for the smallest group ($n = 20$) in the 4-cluster model. The Calinski-Harabasz index (Table S4) was also lower for the 4-cluster model compared to the 3-cluster model (indicating between-cluster dispersion was less and the within-cluster dispersion was increased; also see Figure S1 for t-SNE plot comparisons) and the entropy was greater for the 4-cluster model (Table S4) (higher disorder compared to the 3-cluster model), supporting the decision to reject the 4-cluster model from further analysis. Furthermore, it is recommended that each sub-group sample sizes should at least be between 20 and 30 participants [30].

3.2. Comparison between clusters – 3-cluster model

Cluster 1 was significantly younger than cluster 2 which in turn was significantly younger than cluster 3, with approximately 10 years between each cluster (Table 2). Although means were significantly different, the age dispersions were similarly broad (age ranges of 62, 70, and 70 years for cluster 1, 2 and 3 respectively (Figure S2 and Table S5 reports ranges for all measures)). There was an increasing proportion of females in each cluster, 37 %, 52 % and 59 % respectively (Table 2). Cluster 1 participants had a significantly greater height compared to both cluster 2 and 3 (Table 2). Only cluster 3 had a significantly greater mass compared to cluster 2 (Table 2).

There were participants regardless of age performing similarly within each cluster (Figs. 1–3). For example, in the chair-stand, regardless of age, participants who were in cluster 1 tend to perform just as well across the decades without a sudden drop in later decades (Fig. 2). Clusters 2 and 3 showed dramatic sudden declines in performance across several functional performance measures at the 8th decade; 6MWT, TUDS, chair stand, grip strength and choice stepping reaction time (Fig. 2; Table S6). The general trend of the decade average data also suddenly declines at 8th decade.

The Froude number (walking velocity) was not significantly different between clusters. Furthermore, when broken down into decades per cluster, clusters 2 and 3 show a steady decline in Froude number per decade, whereas cluster 1 shows no general trend until the 5th decade (Table S6). Conversely, the spatiotemporal parameters did significantly differ between clusters (Table 2). Cluster 2 had significantly greater step

Table 1
Participant characteristics.

Decade (yrs)	Sex (m/f) n	Age (yrs) Mean (SD)	Age CoV	Mass (kg) Mean (SD)	Mass CoV	Height (m) Mean (SD)	Height CoV
20–29 (n = 99)	49/50	23 (3)	0.112	67.5 (14.3)	0.212	1.71 (0.11)	0.064
30–39 (n = 100)	50/50	34 (3)	0.092	71.3 (13.4)	0.188	1.70 (0.10)	0.060
40–49 (n = 100)	50/50	44 (3)	0.060	73.9 (14.1)	0.191	1.72 (0.09)	0.055
50–59 (n = 100)	50/50	55 (3)	0.054	73.7 (14.1)	0.191	1.70 (0.08)	0.049
60–69 (n = 100)	50/50	64 (3)	0.039	73.7 (15.7)	0.213	1.68 (0.10)	0.058
70–79 (n = 100)	50/50	73 (3)	0.039	71.1 (11.9)	0.167	1.68 (0.10)	0.058
80–92 (n = 99)	49/50	83 (3)	0.034	70.3 (13.2)	0.187	1.64 (0.09)	0.057
Whole group							
20–92 (n = 698)	348/350	54 (20)	0.370	71.6 (14.0)	0.059	1.69 (0.10)	0.195

Table 2
Comparison between clusters for all measures.

Cluster =>	Mean (SD); CoV: Higher functioning (1) (n=277)	Age average (2) (n=208)	Cautious gait (3) (n=210)	ANOVA	ω²	Pairwise (t, p): 1 vs. 2	1 vs. 3	2 vs. 3
Demographics								
Age (yrs.)	44.7 (16.7); 0.37	55.4 (20.0); 0.36	64.1 (18.0); 0.28	F(2,692) = 70.04, p <.001	.166	-6.452, < .001	-11.733, < .001	-4.922, < .001
Sex (m/f) *	175/102	99/109	73/137	X^2 (2) = 39.22, p <.001	-	-	-	-
Mass (kg)	71.9 (13.2); 0.18	69.7 (13.4); 0.19	73.1 (15.2); 0.21	F(2, 692) = 3.186, p = .042	.006	1.715, .260	-0.935, 1.000	-2.483, .040
Height (m)	1.72 (0.10); 0.06	1.67 (0.09); 0.05	1.67 (0.10); 0.06	F(2, 692) = 26.51, p <.001	.068	5.782, < .001	6.482, < .001	0.640, 1.000
Spatiotemporal								
Walk speed - Froude[a]	0.43 (0.05); 0.11	0.43 (0.07); 0.16	0.43 (0.07); 0.16	F(2, 692) = 0.90, p=0.406	.000	-	-	-
Step length[a]	0.75 (0.03); 0.04	0.78 (0.03); 0.04	0.72 (0.03); 0.05	F(2,692) = 283.63, p<.001	.449	-14.170, < .001	11.190, < .001	23.756, < .001
Stance time[a]	2.10 (0.08); 0.04	2.27 (0.01); 0.05	2.06 (0.10); 0.05	F(2,692) = 301.32, p<.001	.464	-19.825, < .001	4.546, < .001	22.846, < .001
Swing time[a]	1.34 (0.07); 0.05	1.42 (0.08); 0.05	1.29 (0.07); 0.06	F(2,692) = 190.76, p<.001	.353	-11.944, < .001	8.816, < .001	19.449, < .001
Double support time[a]	0.79 (0.08); 0.11	0.88 (0.11); 0.13	0.80 (0.08); 0.10	F(2,692) = 65.88, p<.001	.157	-10.909, < .001	-1.465, < .001	8.861, < .001
Functional								
6MWT[a]	816.9 (75.8);0.09	719.3 (94.6); 0.13	642.3(82.8); 0.13	F(2,692) = 263.97, p<.001	.431	12.687, < .001	22.751, < .001	9.381, < .001
TUDS	21.3 (5.9); 0.28	31.7 (13.1); 0.41	38.0 (12.7); 0.33	F(2,692) = 155.36, p<.001	.308	-10.744, < .001	-17.237, < .001	-6.046, < .001
Chair Stand (number)	25.5 (6.0); 0.24	18.6 (5.4); 0.29	16.7 (4.8); 0.28	F(2,692) = 177.79, p<.001	.337	13.697, < .001	17.591, < .001	3.608, < .001
CSRT-Left (s)	0.60 (0.12); 0.19	0.70 (0.15); 0.21	0.74 (0.14); 0.19	F(2,689) = 65.48, p<.001	.157	-7.507, < .001	-11.026, < .001	-3.295, .003
CSRT-Right (s)	0.58 (0.11); 0.18	0.68 (0.13); 0.20	0.72 (0.14); 0.19	F(2,690) = 80.85, p<.001	.187	-8.468, < .001	-12.202, < .001	-3.494, .002
Strength								
Grip strength[a]	0.37 (0.10); 0.27	0.30 (0.10); 0.33	0.25 (0.08); 0.33	F(2,692) = 91.54, p<.001	.207	8.269, < .001	13.225, < .001	4.615, < .001
Ankle PF. Isometric[a]	0.44 (0.09); 0.20	0.39 (0.09); 0.24	0.34 (0.09); 0.27	F(2,685) = 65.91, p<.001	.159	5.602, < .001	11.458, < .001	5.504, < .001
Ankle DF. Isometric[a]	0.29 (0.07); 0.25	0.25 (0.08); 0.30	0.22 (0.07); 0.32	F(2,691) = 68.81, p<.001	.165	5.941, < .001	11.777, < .001	5.448, < .001
Knee Flex. Isometric[a]	0.14 (0.04); 0.25	0.11 (0.03); 0.28	0.10 (0.03); 0.32	F(2,675) = 110.76, p<.001	.245	8.935, < .001	14.575, < .001	5.310, < .001
Knee Ext. Isometric[a]	0.27 (0.07); 0.26	0.21 (0.07); 0.31	0.18 (0.06); 0.33	F(2,679) = 112.20, p<.001	.246	8.351, < .001	14.807, < .001	6.037, < .001
Quality of life								
AQOL (utility)[b]	0.87 (0.10); 0.12	0.84 (0.11); 0.13	0.83 (0.11); 0.14	F(2,692) = 7.89, p<.001	.019	2.837, 0.014	3.731, <.001	0.829, 1.000
AQOL (physical)[c]	0.86 (0.11); 0.13	0.81 (0.12); 0.15	0.78 (0.15); 0.19	F(2,692) = 21.15, p<.001	.055	3.668, <.001	6.426, <.001	2.570, .031
AQOL (mental)[d]	0.56 (0.16); 0.29	0.52 (0.15); 0.29	0.52 (0.15); 0.28	F(2,692) = 5.35, p=.005	.012	2.601, .028	2.908, .011	0.281, 1.000
Physical activity								
IPAQ (total)[e]	6074.8 (5000.5); 0.82	5133.9 (4867.7); 0.94	5191.1 (4790.8); 0.92	F(2,692) = 2.89, p=.056	.005	-	-	-

Colours around groups 1, 2, and 3 correspond to the cluster colours within Figs. 1, 2, and 3; Effect size interpretation: Small effect, ≈ 0.01; Medium effect., ≈ 0.06; Large effect, ≈ 0.14; Pairwise comparisons were corrected using Bonferroni; *Chi-squared test for sex between clusters; 6MWT, 6 min walk test; [a] Normalised - Dimensionless; AQOL, Assessment of Quality of Life; [b]AQOL (utility), global score; [c]AQOL(physical), physical super-dimension (comprised of independent living, pain, and physical senses); CoV, coefficient of variation; CSRT, choice reaction step test; [d]AQOL (mental), mental super-dimension (comprised of; mental health, self-worth, relationships, happiness and coping dimensions); [e] IPAQ, The International Physical Activity Questionnaire. Total physical activity in the past week was calculated in MET-minutes; PF, plantarflexor; DF, dorsiflexor; TUDS, timed up and down stairs.

length, stance time, swing time, and double support time compared to clusters 1 and 3 (Fig. 1 & Table 2). Across all spatiotemporal parameters cluster 1 was similar to the decade average (Fig. 1), but cluster 3 had consistently significantly worse values (Table 2) and from hereon in was labelled as ‘cautious gait’ cluster.

Functional measures were all significantly different between clusters (Table 2). Cluster 1 was classed as ‘higher’ functioning (i.e. increased 6MWT; reduced TUDS; greater number of chair stands; greater grip

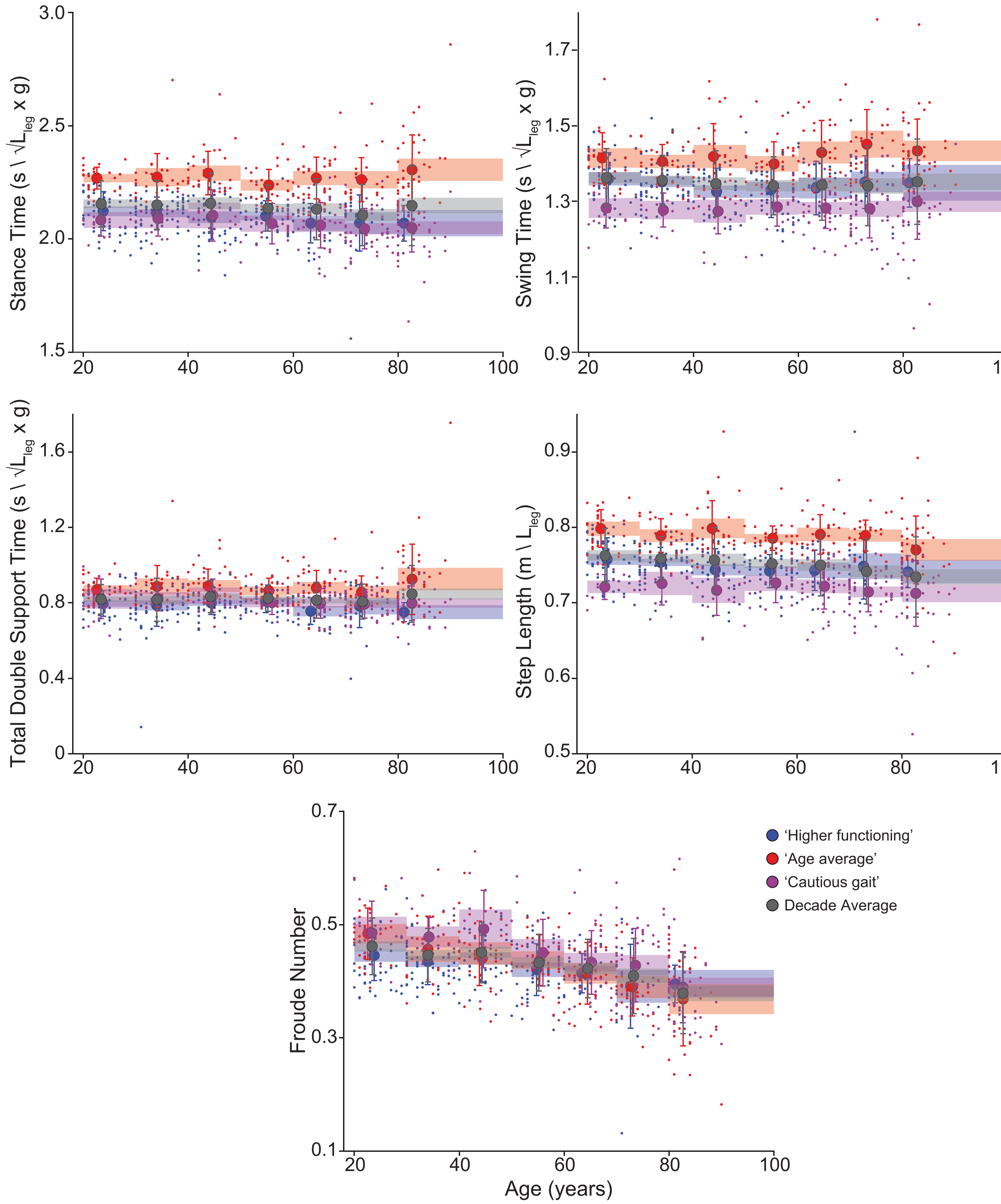

Fig. 1. Spatiotemporal data across the ages per cluster. Each individual data point is plotted and coloured by its cluster. Averages per cluster, and overall decade averages are superimposed in the scatter plot with vertical bars representing 1 standard deviation and transparent rectangles show the confidence intervals for that group and decade. Cluster 1 refers to the "higher-functioning" group, cluster 2 is the "age average" and cluster 3 is the "cautious gait" group.

strength; and quicker reaction times) compared to clusters 2 and the 'cautious gait' cluster (3) (Fig. 2). Cluster 2 tended to map closely to the overall decade average (Fig. 2) and so was classed as the 'age average' cluster. There was a significant reduction in performance from cluster 1-to-2-to-3 (Table 2). 'Higher' functioning participants were consistently better performing than the decade average for each measure (Table S6). This trend becomes even stronger for 60-year-olds and older where the gap widens between 'higher' functioning and 'age average' and 'cautious gait' clusters and the overall decade average. Within the 6MWT, 'higher' functioning cluster maintains consistent performance across all decades unlike the other clusters (Table S6). Conversely, the 'cautious gait' cluster tends to underperform for all measures compared to the decade averages. Within the 'cautious gait' cluster, younger adults are performing just as poorly, or worse than older adults in the 'cautious gait' and 'age average' clusters (e.g. 6MWT, Fig. 2). Grip strength was also progressively and significantly reduced from the 'higher functioning' to the 'cautious gait' cluster (Fig. 2 & Table 2). Grip strength across the decades showed a decrease in performance for 'age average' and 'cautious gait' clusters and the decade average (Fig. 2; Table S6). Conversely, the 'higher functioning' cluster only showed a decrease between the 2nd – 6th decade where this trend plateaued, and grip strength remained stable (Fig. 2; Table S6). Therefore, within the 8th decade there was a large difference in grip strength between 'higher' functioning (0.305 (0.057) [mean (SD)]) and 'cautious gait' clusters (0.213(0.073)).

Strength measures significantly differed between each cluster

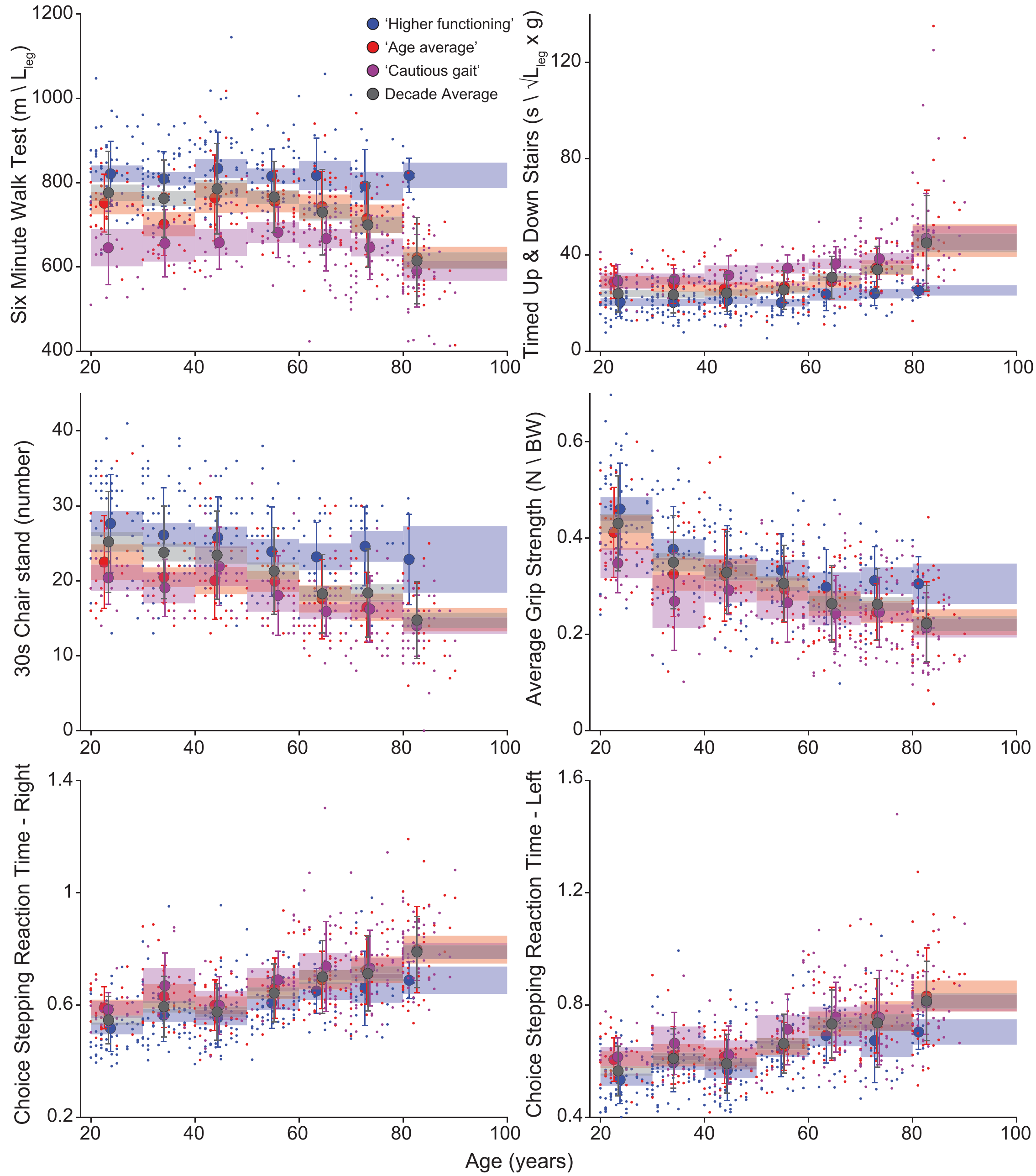

Fig. 2. Functional performance data across the ages per cluster. See Fig. 1 for details on colours and symbols. Cluster 1 refers to the "higher-functioning" group, cluster 2 is the "age average" and cluster 3 is the "cautious gait" group.

(Table 2). There was a decrease in strength from cluster 1-to-2-to-3 (Fig. 3). The 'higher' functioning clusters' lower limb strength outperformed all other clusters (Fig. 3) and the decade averages (Table S6). Lower limb strength shows a similar trend across clusters and decades to grip strength. For lower limb strength 'higher' functioning cluster plateaued in performance in the later decades whilst 'age average' and 'cautious gait' clusters and the decade averages continued to decline with age (Fig. 3). Ankle plantarflexion strength did not show this trend and instead remained relatively consistent within a cluster across the decades.

Quality of life (QoL) was significantly greater for the 'higher' functioning cluster across all measures (utility, physical and mental) compared to 'age average' and 'cautious gait' clusters (Table 2). QoL-utility and QoL-mental did not statistically differ between the 'age average' and 'cautious gait' clusters. QoL-physical was statistically different between the 'age average' and 'cautious gait' clusters (Table 2). Within the last decade the 'higher functioning' cluster shifted towards better values of QoL, whilst the 'age average' and 'cautious gait' clusters maintained or dropped their scores (Fig. 3; Table S6). Total IPAQ did not differ between clusters (Table 2), but the 'higher functioning' cluster tended towards higher IPAQ values across each decade (Fig. 3; Table S6), however, the CoV for IPAQ scores were very high (0.82–0.92; Table 2).

4. Discussion

We aimed to establish if patterns of function can be identified from an individual's gait, using a clustering approach on "normalised" spatiotemporal and functional performance data, without the need for age stratification. Based on previous clustering gait papers [16] we initially expected a cluster to form around younger adults (i.e. 20–30 years) with several older mixed age (>60 years) clusters. In contrast to

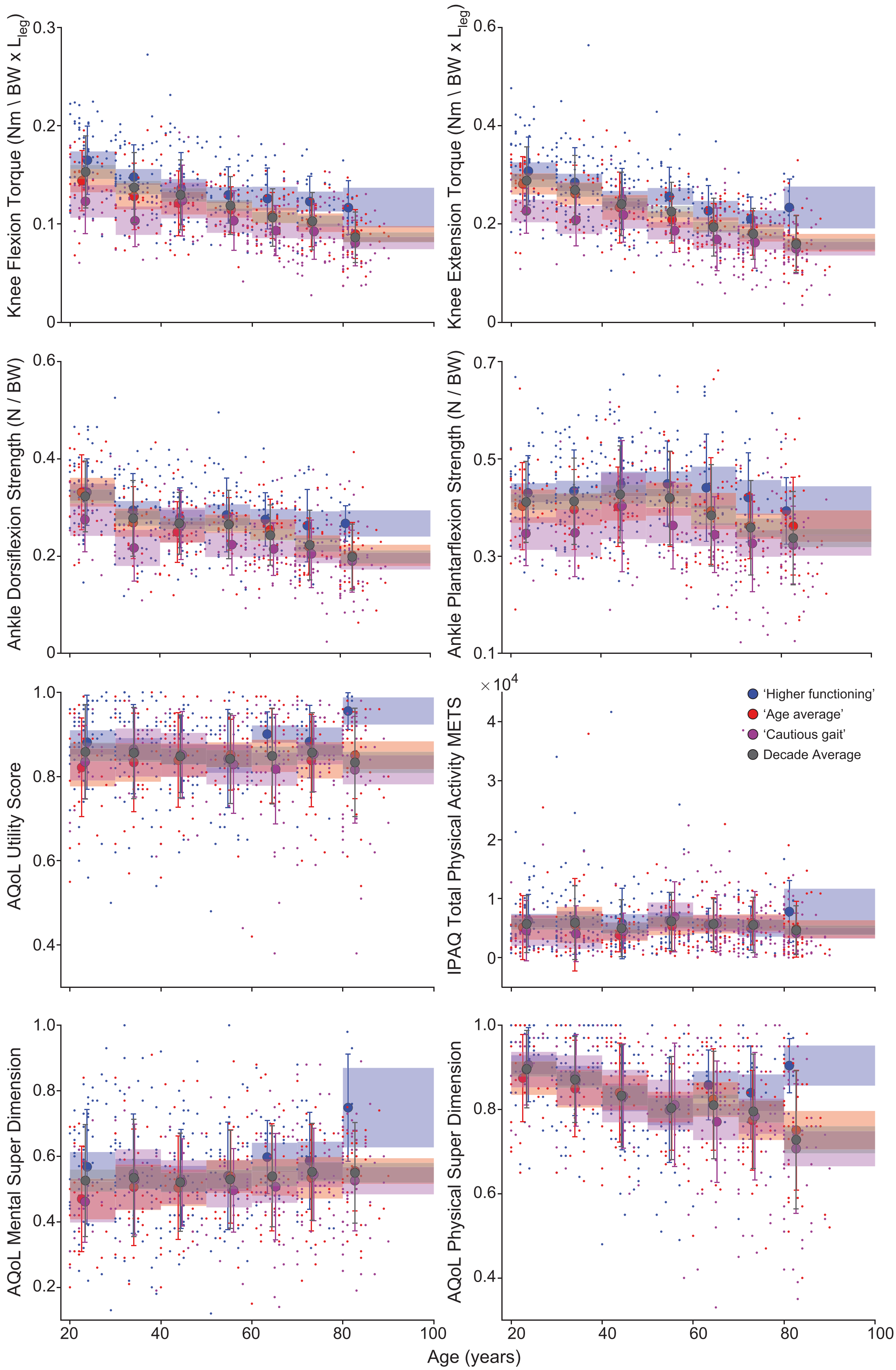

Fig. 3. Strength and Quality of life data across the ages per cluster. See Fig. 1 for details on colours and symbols. Cluster 1 refers to the "higher-functioning" group, cluster 2 is the "age average" and cluster 3 is the "cautious gait" group.

these predictions, we identified three clusters representing 'higher functioning' (cluster 1), 'age average' (cluster 2), and 'cautious gait' (cluster 3) clusters. The stability of these cluster centres was quite high with a misclassification of 3.8 %, comparable to other studies[12,14,34] and indicates that the clusters were consistently reproducible. This therefore suggests that age may just be a number, and that to determine functional movement ability we should not be stratifying by age before assessing an individuals' function.

Walking speed has been consistently used as a measure of gait functional health (i.e.[35]) our results here question the validity of assessing by walk speed and age only via recommended reference values (i.e.[36]). Here, we show no significant changes in walk speed across our clusters, more specifically all our clusters averaged a Froude number of 0.43 (Table 2). Furthermore, each cluster showed a similar wide dispersion of age ranges (20–92 years) with only a 10-year average age difference between clusters ('higher functioning', 44.7 (16.7) years; 'age average', 55.4 (20.0) years; 'cautious gait', 64.1 (18.0) years). Therefore, these clusters appear independent of walking speed and include a wide range of ages. Although there is a trend of reducing walk speed with age (Fig. 1) across all clusters, we suggest that walk speed and age alone are not the over-riding factors indicating functional health and treating them as such may bias findings. Indeed, walking speed is impacted by a variety of aspects [37], and 'feelings of youthfulness' can also impact walking speed [38] suggesting that these parameters should not solely be used to assess gait health.

Our data show that older adults are not a homogeneous group and as such should not be grouped into one cohort. Ageing is not uniform and with longevity increasing [39] forcing a heterogenous group into homogeneous age groupings will likely hide any functional trends. Other approaches partitioning groups by specific age categories [9] or decades [10] (which have been recommended i.e. [10]) are likely to also hide functional trends based on our analysis. Similarly, our middle-aged participants, an often under reported age group, do not form a homogenous group. Here middle-aged participants in the 'cautious gait' cluster underperformed in functional and strength measures compared to a) their age matched counterparts in the 'higher functioning' and 'age average' clusters and, b) older adults in the 'higher functioning' cluster. It is possible that by clustering and identifying 'poor' middle-age performers in function and strength, which will impact physical function in later life, and intervening earlier will facilitate and slow functional decline [40]. Therefore, future work should investigate the use of cluster group identification on functional and strength capabilities during middle-ages.

Our clusters lead to the notion of 'successful ageing' – are those in 'higher functioning' (cluster 1) successful agers compared to those in 'cautious gait' (cluster 3)? Successful ageing focuses on the lack of chronic diseases, physical disabilities and risk factors for disease in older age, as well as good mental health, cognitive function and social engagement [41]. The 'higher functioning' group had better functional, strength and psychosocial outcomes compared to all other clusters (Table 2). The 'higher functioning' cluster also tended to 'outperform' the decade average across ages and particularly for >60 years (Figs. 1–3). Yet there is no universal definition or objective measure of successful ageing [42]. Those in the 'higher functioning' cluster are arguably the 'healthier' group based on their outcome measures as they are linked with increased chances of successful aging [43]. Care, though, does need to be taken with the term 'successful ageing' as it suggests there are "winners" and "losers". This is problematic as older adults define successful ageing by their own criteria [44], with 39 % contradiction between self-assessed and the criteria set out by Rowe and Kahn [41,44].

Despite the 'higher functioning' cluster having improved functional and well-being measures its' spatiotemporal parameters do not fit within the time nor length gait domains. A time-domain strategy uses changes in the temporal parameters, conversely the length-domain strategy alters spatial parameters [45]. We know that a certain amount of variability enables successful and healthy movement [46]. It is also clear that both increased and reduced variability can have detrimental effects on movement resulting in adverse events [47-49]. The 'higher functioning' cluster may be able to maintain this optionality (using neither a time domain nor temporal domain strategy) due to their continued higher strength parameters across the decades (Fig. 3). Knee and ankle strength outcomes were at a relatively consistent level providing protection [35,50,51], improved gait health [52], and lower likelihood of frailty in older age groups [53,54]. Therefore, although the 'higher functioning' cluster spatiotemporal outcomes had unremarkable characteristics, this may be advantageous, providing movement strategy optionality due to maintenance of greater strength across the decades.

Conversely, the 'cautious' cluster had shorter step length, and reduced stance and swing times (Fig. 1), therefore using the 'time-domain' or cadence strategy, often associated with mobility/functional limitations [45]. This strategy due to its higher propulsive impulse requirements leads to a lack of optionality for increasing speed [45]. Furthermore, shorter step and stride lengths are associated with falls and other negative events (i.e. increased caring needs, physical disability) [55,56], which may suggest that the 'cautious gait' cluster are at higher risk of an adverse event. As spatiotemporal variability is limited this may result in the reduced performance in the strength, functional, and well-being measures (Figs. 2 and 3; Table 2). The 'age average' cluster had longer step lengths and step times – more fitting a length-domain strategy, yet this was not accompanied with greater functional performance. The 'age average' cluster most closely tracked the decade averages for functional performance (Fig. 2) and strength (Fig. 3) measures. The 'age average' cluster, similarly to the 'higher functioning' cluster, had spatiotemporal parameters that are considered clinically stable gait, but the lack of greater functionality is likely due to lower strength outcomes (Fig. 3). The lower strength outcomes may limit their options if they experience changes to physical or mental health.

In short, we are unable to say if these clusters reflect successful ageing i.e., we cannot suggest that being in a 'higher functioning' cluster means less comorbidities etc, as these data were not collected as part of 1000 Norms Project. But our analyses do reveal the potential bias of ascertaining functional capacity by walking speed and age alone. Instead, we suggest that "age is just a number", as some older adults ('higher functioning' cluster) perform just as well, if not better, than some younger adults ('cautious gait' cluster). Future work should identify whether an individual remains in a specific cluster throughout the lifespan or can move fluidly between clusters. Our work has identified that comparing or separating individuals, based on gait parameters, into aged groups is not appropriate. We now need to focus on clinically identifying cluster membership, cluster membership impact on longitudinal health outcomes and the fluidity between clusters across the lifespan.

CRediT authorship contribution statement

Marnee J McKay: Writing – review & editing, Funding acquisition, Data curation. **Matthew J.D Taylor:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Joshua Burns:** Writing – review & editing, Funding acquisition, Data curation. **Jennifer Baldwin:** Writing – review & editing, Funding acquisition, Data curation. **Aleksandra V Birn-Jeffery:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of Competing Interest

"I have nothing to declare".

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gaitpost.2025.08.080.

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