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Age-related gait standards for healthy children and young people: The GOS-ICH Paediatric Gait Centiles

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ABSTRACT

Objective To develop paediatric gait standards in healthy children and young people.

Methods This observational study builds on earlier work to address the lack of population standards for gait measurements in children. Analysing gait in children affected by neurological or musculoskeletal conditions is an important component of paediatric assessment but is often confounded by developmental changes. The standards presented here do not require clinician expertise to interpret and offer an alternative to developmental tables of normalised gait data. Healthy children aged 1-19 years were recruited from community settings in London and Hertfordshire, U.K. The GAITRite® walkway was used to record measurements for each child for velocity, cadence, step length, base of support, and stance, single and double support (as percentage of gait cycle). We fitted generalized linear additive models for location, scale and shape (gamlss).

Results We constructed percentile charts for seven gait variables measured on 624 (321 males) contemporary healthy children using `gamlss` package in R. A clinical application of gait standards was explored.

Conclusion Age-related, gender-specific standards for seven gait variables were developed and are presented here. They have a familiar format and can be used clinically to aid diagnoses, and to monitor change over time for both medical therapy and natural history of the condition. The clinical example demonstrates the potential of the GOS-ICH Paediatric Gait Centiles (GOS-ICH PGC) to enable meaningful interpretation of change in an individual's performance, and describes characteristic features of gait from a specific population throughout childhood.

Keywords: gait, child development, gamlss, walking velocity, cadence, base of support, double support.

INTRODUCTION

Gait is widely assessed in paediatrics, as achievement of walking is a developmental milestone and reflects maturation of a healthy nervous system (1). Changes in gait patterns occur as a child matures and grows, but may also reflect pathological changes in neurological or musculoskeletal systems. Gait assessment may contribute to diagnosis, describe the natural history, or categorise the severity of pathology (2, 3). It is also used as an outcome to demonstrate the efficacy of surgery, therapy or medications (4, 5).

Clinicians need a robust measure of gait which is valid and reliable in children, and sufficiently specific to detect changes in performance over time. However, there is a lack of easy to use, objective assessment for clinical settings. Charts displaying gait measurements as a function of height, or speed, have been proposed to simplify interpretation (6, 7). However, normative data for clinical gait measures is typically tabulated (5). Developmental centile charts of gait measures offer a solution to assess individual children's evolution.

In this paper we construct age-related, gender-specific standards that reflect key determinants of normal gait (8): velocity, cadence, step length, base of support, and stance, single and double support as percentage of the gait cycle. Self-selected velocity was used because it is a good surrogate of functional capacity, and is the least variable walking speed (9). Cadence, or rate of stepping, has a complex interaction with velocity and stride length. It appears that children use characteristic combinations of cadence and stride length to modify their speed (6). Step length, base of support, and double support together alter the challenge to equilibrium

during gait, and may reflect balance ability. Base of support was therefore included despite concerns about the reliability (10, 11).

We build on the work of Alderson and colleagues who used the LMS method (6), to produced reference centiles for gait measures from a sample of 137 children (81 male) aged between 4 and 14 years (12, 13). The centiles reflect the distribution of each gait measurement as it changes according to a covariate, age. In this paper we fit models in the `gamlss` family. These generalized additive models for location, scale and shape (14), allow fitting of smooth age-related changes in kurtosis as well as in location, dispersion and skewness.

This study aimed to develop paediatric gait standards for healthy children and young people. The proposed standards enable clinicians to objectively quantify improvements associated with medical therapies, but, crucially, to also identify deterioration in affected children leading to timely intervention.

METHODS

Participants

Typically developing children between the ages of 1 – 19 years were recruited from local schools, play groups, activity and sports clubs in Greater London and Hertfordshire, UK. Parents of pre-school children were approached directly by the researcher, whilst older children had information packs distributed by class teachers or group leaders. Children were recruited between 2004-2006 and 2012-2014 using a convenience sampling approach stratifying by age and sex. We aimed to recruit at least 15 children of each sex in one-year age groups. Data from 540 children in 18

age groups was considered to be sufficient to produce acceptable standards. Data on participants' ethnicity were not collected.

Two experienced paediatric physiotherapists (LA and JK) collected the data using two Platinum GAITRite® walkways, with software versions 4.3 and 4.7 (CIR Systems Inc). Summary data were compared to ensure consistency between walkways and testing epochs. To participate in the study the children had to be ambulant and able to walk 100m independently. Children who had undergone surgery or sustained a lower limb injury in the previous six months, or had existing neurological or orthopaedic diagnoses were excluded. Ethical approval for the study was provided by the Barnet Enfield and Haringey REC 04/Q0509/49 in October 2004 and Bloomsbury Research and Ethics Committee REC 11/LO/1889 January 2012. Written consent was obtained from the parents or carer, or the children themselves if they were over 16 years old.

Equipment

The GAITRite® (CIR systems Inc.) is a 5m electronic pressure sensor walkway connected via USB to a computer (15). 18 432 sensors are embedded in a grid with an active measurement area 61cm by 488cm. Mechanical pressure from foot contact activates the sensors which are sampled at a rate of 80Hz, and data is used to generate distance and timed gait data. It has been shown to be an effective research tool (16).

Measurements

The GAITRite® software processes raw data into footfalls and presents temporal and spatial (TS) gait variables. Concurrent validity of temporal and spatial measures has been supported with both 3D motion analysis and a wearable sensor (17, 18).

Reliability has been explored in adults, with reported limits of agreement +/- 11cm/sec for velocity, and Coefficient of Variation (CV_{ME}) 1.8-3.5% (16, 19). The level of precision for velocity measurements in children is comparatively larger, but still considered acceptable; 4-11 years CV_{ME} 7.5-7.8% (11) and 4-14 years CV_{ME} 10.8% (10). The CV_{ME} 's reflect the normal variation in paediatric gait patterns (10, 11) which is incorporated within the standards.

Base of support and foot progression angle are associated with wide limits of agreement in all age groups. The precision of these measurements is affected by the spatial resolution of the GAITRite® walkway, a particular problem in young children. In the current paper, base of support was included to allow comparison with previous work, but foot progression angle was omitted as developmental changes have been previously described in detail and have a relatively large measurement error (20, 21). Ultimately the seven measurements analysed in this study are widely reported gait measurements (5, 22), and were selected to balance clinical utility with reliability.

Normalisation

Normalisation of gait data has been proposed to remove the influence of changing body dimensions on gait measures, thus reducing the age-related variability (23, 24). This process of normalisation assumes a simple relationship between, for example, leg length and step length, and fails to consider the relative contributions of

neuromaturation and anthropometric growth and extrinsic factors that influence developmental trajectory (25, 26).

The use of continuous standards to describe the distribution of specific gait variables offers an alternative analysis. This allows the clinician to look for generality in the distribution, not specificity, and avoids the need to normalise or produce non-dimensional values. A child's gait can be interpreted against the continuous standards and any changes in performance with injury, therapy or growth can be interpreted within the context of normal developmental changes.

Study protocol

We followed the protocol of Alderson (12). The GAITRite® walkway was positioned with sufficient space to ensure that acceleration/deceleration occurred outside the active recording area. Following one practice walk, children performed three walks at each of self-selected, fast and slow walking speeds. In this paper, we only analyse self-selected walking speed which was always recorded first. All participants walked unaided with bare feet to remove the influence of different footwear (27).

Performance of three consecutive walks at each speed ensured that an adequate number of steps (8-12 steps) were recorded to provide an accurate representation. Previous work had shown eight steps was a sufficient number to stabilize variation in key walking measurements (12). Footfalls touching an edge of the walkway were excluded, as were walks with less than four complete steps (12, 15).

The GAITRite® software automatically combines the three repetitions and provides an average which we used for analysis. Previous work comparing unprocessed step values with averages of three repeat walks demonstrated similar means, with greater variability associated with individual step data (12). Following testing for any significant differences, the data for left and right sides were combined. The average of the two sides was used for step length and base of support. Double support, single support, and stance percent of gait cycle were expressed as the maximum value of either side as they were already standardized by gait cycle.

Statistical methods

The LMS method summarises the age-related distribution of a particular measure, using three curves describing location, coefficient of variation and degree of skewness (28). These curves are fitted to the data as cubic spline, and the extent of smoothing can be expressed in terms of equivalent degrees of freedom, which reflects a trade-off between goodness-of-fit and smoothness (12, 29). Models in the `gamlss` class allow for a curve on a fourth shape parameter, normally kurtosis. We used the four-parameter Box-Cox- t distribution (14, 30). The optimal number of degrees of freedom in each of the four components of the models was chosen by minimising the Bayesian Information Criterion (BIC) (31). All calculations were performed using the R language and environment for statistical computing, version 3.4.2 (32).

Gait measurements collected as part of an observational study of children with spinal lipoma were processed using the same protocol (25). Data were imported to R and

plotted on the corresponding standards, to illustrate the clinical application of the standards.

RESULTS

We collected data from 624 children (303 girls and 321 boys). It was more difficult to recruit in the first two age groups, as many didn't meet the inclusion criteria. We analysed seven gait variables: Velocity (cm/s), cadence (step/min), step length (cm), base of support (cm), and single support, double support, and stance (percent gait cycle). Data from one child was excluded as he/she was a new walker and failed to reach a minimum velocity to enable analysis. Table 1 shows demographics and age- and gender-related means and standard deviations of anthropometric data and step counts. We observed a larger variation in step counts in the very young participants who were less able to follow the protocol and more likely to step outside the recording area.

Table S1 in supplementary material shows the optimal degrees of freedom for each component of the `gamlss` models for each variables. The resulting models were judged to balance an appropriate degree of smoothing and fit of the curves to the data, however an adjustment reducing one degree of freedom in each gender was applied to base of support to avoid over fitting. The age-related and gender-specific standards are presented in Figures 1a-c for velocity, cadence and step length, and in supplementary material for base of support, stance, single and double support (Figures S1a to S1d). Tables S2a to S2g in supplementary material show the gender-specific centiles for selected ages.

Figure 2 shows sequential velocity measurements for a child with spinal lipoma, which remained between the 25th and 75th centiles. Figure 3 plots velocities for a group of 18 children with spinal lipoma (33). In this example, older children's velocities tended to be tightly concentrated below the mean, whilst patients under 10 years of age had a more typical spread.

DISCUSSION

Assessment of the outcome of therapeutic interventions, or of disease progression in paediatrics is increasingly considered within the framework of the International Classification of Functioning, Disability and Health in Youth and Children ICF-CY (34, 35). Mobility and gait analysis are important outcomes within the activity domain, however user-friendly, standardised, quantitative tools have remained elusive, and was the driver for developing the GOS-ICH Paediatric Gait Centiles presented in this paper.

These standards describe typical changes in gait performance throughout childhood, whilst accommodating the observed variation in gait measurements as children develop at different rates with different morphologies. This analysis builds on a previous study (12, 13), which fitted age-related standards to data from 137 children. To our knowledge, the sample described in the current study (624) is the largest study analysing paediatric GAITRite® variables. In comparison the 1000 norms project included 300 Australian children aged from three to nineteen years (5).

Our age-continuous analysis offers something novel compared to group-based analysis, (36, 37). Measurement centiles allow comparison of performance to a

standard rather than another discrete data point with associated measurement error. Sequential changes in an individual's performance that are less than described limits of agreement (10, 16, 19), may still be clinically relevant when taken together and tracked against population centiles (see Figure 2).

The increased variability in measurement of base of support is well recognised, reflecting both magnitude of measurement relative to tool precision, and normal variation (38). This was reflected in the optimised population standards. An adjustment was carried out to correct for overfitting in this variable only.

The clinical utility of these standards depends on their simplicity and ease of use. Developmental changes can be quickly understood by the clinician, and importantly, by families. Subtle gender differences in gait during puberty can also be explored, complementing population studies with wider age ranges exploring gait changes across the lifespan (5). These standards are also able to identify specific deviations from a typical developmental trajectory across a broad spectrum of disorders. Clinical applications include the ability to characterize diseased children, to screen for deterioration, or to explore effectiveness of interventions such as surgery, novel drug therapy, or rehabilitation.

Simplified gait standards from the earlier analysis of 137 children, have been used to track performance in children with haemophilia, to explore the cumulative impact of progressive joint bleeds on gait, and to allow intervention before secondary gait compensations emerge (2). The standards have also shown potential to track the performance of children with spinal lipoma (Figure 3), and to support the decision

making surrounding untethering surgery, and guide rehabilitation (33). Medical management of metabolic disorders relies on accurate functional gait outcomes, often used as primary endpoints in the evaluation of efficacy of novel therapies; for example enzyme replacement and gene therapy. The GAITRite® measurements can easily be combined with capacity measurement, such as the six-minute walk test (39), and with wearable gait trackers, a combination of outcomes that are strong contenders for inclusion in future trials.

Limitations

Children living in different geographical areas may exhibit different developmental gait patterns. These standards are not necessarily representative of the United Kingdom (UK) population. Summary gait statistics are influenced by differences in morphology (40). Activity patterns may also contribute to differences; children recruited from the Australian population (5) may be more active than their UK counterparts. Despite potential differences in sample characteristics, the distribution of data at each specific age is comparable with the summary mean and dispersion data reported elsewhere (5).

Comparisons between individual children require normalization, but this is not necessary to construct standards for healthy children. In the same way that head circumference is not standardised to height percentiles, we developed standards that were independent of body size to prevent the loss of the “depth” of the normal data.

Random sampling was not attempted because it is not pragmatic to recruit large numbers of healthy children as part of a population sampling frame.

CONCLUSION

This paper presents a simple way for clinicians describing and assessing gait patterns in healthy children. This has been shown to be a useful way to screen children with different pathologies to identify early changes in gait. The benefit of continuous analysis of gait changes enables an individual's performance to be tracked against expected development. Similar to growth centiles, the clinician does not need to consult detailed tables to compare a measurement to a specific mean and measure of dispersion, but can identify at a glance how the child's gait is currently functioning and how this has changed relative to previous measurements.

What is known:

- 1) Achievement of walking reflects maturation of a healthy nervous system and is a key rehabilitation goal, and outcome in clinical trials
- 2) Normal developmental changes in gait confound the interpretation of performance change in response to therapy or associated with recovery
- 3) Accurate measurement of gait which facilitates clinical interpretation and provides objective outcomes for clinical trials is challenging

What this paper adds:

- 1) Novel analysis using the `gamlss` family of models to develop new standards for paediatric gait, to facilitate interpretation of data in a clinical setting
- 2) Age-related, gender-specific standards for seven gait variables are presented in a familiar display and allow clinicians to objectively quantify improvements associated with medical therapies
- 3) Gait standards are a useful tool to track natural history and identify deterioration to allow timely interventions

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Tables and Figures

Table 1 – Age- and gender-related means and standard deviations of anthropometric variables.

Table S1 (supplementary) – Degrees of freedom for splines in `gamLSS` components in each variable

Tables S2a to S2g(supplementary)– summary of standards by age and gender

Figures 1a to 1c – Age-related standards by gender for velocity, cadence and step length

Figure 2 – Sequential velocity measurements of a boy with spinal lipoma against population standard

Figure 3 – Cross-sectional velocity measurements for 18 boys with spinal lipoma against population standard

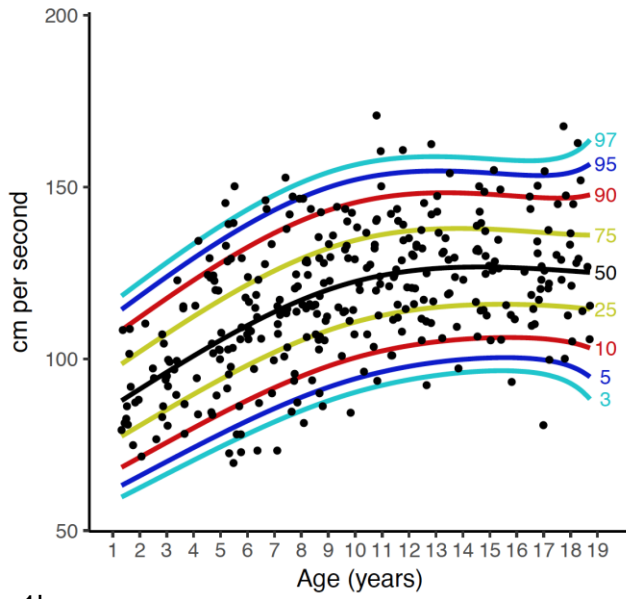
Figures S1a to S1d (supplementary) – Age-related standards by gender for base of support, stance, single and double support

Table 1: Age- and gender-related means and standard deviations of anthropometric variables

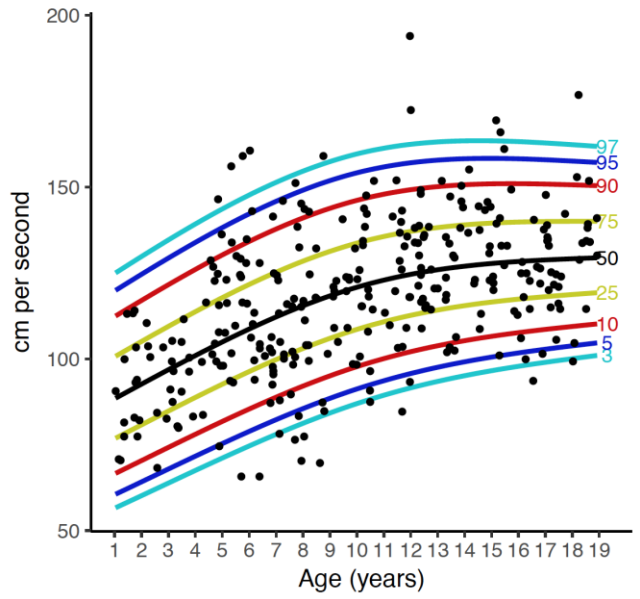
AGE	Freq*		Age (years)		height (cm)		weight (kg)		left leg length (cm)		right leg length (cm)		leg length difference		step count (No of steps)	
	F	M	F	M	F	M	F	M	F	M	F	M	F	M	F	M
1	14	12	1.53 (0.29)	1.59 (0.19)	77.83 (3.28)	80.33 (3.39)	10.84 (0.88)	12 (1.67)	34.86 (2.11)	36.19 (2.15)	34.86 (2.11)	36.19 (2.15)	0 (0.14)	-0.042 (0.14)	36.36 (17.3)	37.92 (22.13)
2	8	10	2.46 (0.40)	2.63 (0.31)	86.12 (4.54)	92.35 (5.24)	13.33 (1.53)	14.56 (1.88)	39.5 (3.21)	41.85 (3.56)	39.5 (3.21)	41.85 (3.56)	0 (0.00)	0 (0.00)	33.62 (14.9)	20.8 (6.37)
3	12	14	3.44 (0.28)	3.35 (0.26)	94.62 (3.49)	98.25 (3.97)	15.09 (1.04)	16.23 (2.35)	44.83 (2.43)	43.96 (4.9)	44.83 (2.43)	43.96 (4.9)	0 (0.00)	0 (0.0)	32 (11.08)	26.29 (10.54)
4	16	19	4.59 (0.50)	4.63 (0.29)	106.11 (6.01)	107.97 (5.34)	17.89 (3)	19.43 (3.75)	51.25 (4.2)	50.08 (3.85)	51.25 (4.2)	50.08 (3.85)	-0.08 (0.71)	0.06 (0.42)	25.56 (6.09)	26 (4.18)
5	19	23	5.47 (0.31)	5.49 (0.27)	111.83 (4.55)	114.65 (3.95)	19.84 (1.23)	21.99 (3.74)	54.86 (2.71)	55.15 (3.36)	54.86 (2.71)	55.15 (3.36)	0.16 (0.34)	0.02 (0.24)	24.37 (5.27)	23.7 (5.35)
6	22	19	6.4 (0.45)	6.35 (0.35)	117.16 (5.64)	120.52 (4.57)	22.09 (2.97)	24.16 (2.91)	57.44 (5.03)	58.08 (3.98)	57.44 (5.03)	58.08 (3.98)	-0.09 (0.23)	-0.12 (0.55)	25.68 (5.99)	22.32 (3.76)
7	23	23	7.49 (0.3)	7.49 (0.3)	124.32 (4.84)	127.69 (5.6)	26.32 (4.1)	27.17 (3.61)	64.28 (4.02)	63.69 (5.39)	64.28 (4.02)	63.69 (5.39)	-0.02 (0.35)	-0.01 (0.17)	23.09 (5.88)	23.3 (5.89)
8	20	31	8.21 (0.54)	8.44 (0.38)	132.14 (7.9)	132.97 (5.7)	32.47 (7.92)	31.37 (5.3)	66.94 (4.67)	66.81 (4.6)	66.94 (4.67)	66.81 (4.6)	-0.03 (0.26)	-0.19 (0.46)	22 (4.77)	20.26 (5.54)
9	14	18	9.47 (0.29)	9.47 (0.37)	137.92 (6.4)	136.13 (7.09)	34.64 (7.62)	31.71 (5.42)	71.05 (9.4)	69.97 (6)	71.05 (9.4)	69.97 (6.0)	-0.04 (0.31)	-0.05 (0.21)	20.07 (3.79)	19.39 (2.77)
10	20	24	10.31 (0.18)	10.53 (0.38)	141.56 (6.95)	145.08 (5.6)	38.56 (9.28)	37.69 (5.63)	74.38 (6.01)	75.83 (5.6)	74.38 (6.01)	75.83 (5.6)	0.05 (0.22)	0.02 (0.50)	17.95 (4.39)	16.21 (3.41)
11	20	19	11.64 (0.26)	11.58 (0.21)	150.35 (5.9)	148.66 (6.5)	43.79 (8.82)	40.83 (7.09)	79.71 (4.07)	77.21 (5.88)	79.71 (4.07)	77.21 (5.88)	0.25 (1.02)	0 (0.17)	17.45 (4.14)	17.53 (3.2)
12	21	21	12.4 (0.19)	12.46 (0.28)	151.3 (7.8)	153.31 (7.74)	46.17 (11.48)	45.66 (7.12)	82.08 (5.47)	80.54 (5.43)	82.08 (5.47)	80.54 (5.43)	0.09 (0.25)	-0.02 (0.11)	18.29 (4.78)	17.67 (2.94)
13	18	16	13.45 (0.28)	13.37 (0.32)	159.61 (6.85)	159.53 (7.39)	52.22 (9.98)	52.31 (13.04)	85.61 (5.3)	84.89 (6.03)	85.61 (5.3)	84.89 (6.03)	-0.11 (0.46)	0.03 (0.13)	16.5 (2.94)	15.31 (3.11)
14	15	18	14.57 (0.33)	14.65 (0.22)	160.77 (5.64)	169.08 (5.75)	56.38 (10.17)	61.62 (8.09)	86.08 (4.13)	89.21 (5.68)	86.08 (4.13)	89.21 (5.68)	-0.17 (0.67)	-0.03 (0.12)	17.93 (3.35)	17 (3.03)
15	14	12	15.36 (0.27)	15.42 (0.3)	163.07 (9.26)	168.12 (6)	57.93 (10.28)	61.64 (12.72)	87.68 (5.49)	90.9 (5.21)	87.68 (5.49)	90.9 (5.21)	0.14 (0.36)	-0.04 (0.45)	15 (5.55)	15.67 (2.23)
16	16	15	16.44 (0.33)	16.7 (0.2)	164.59 (6.83)	174.67 (6.56)	59.38 (7.31)	69.73 (10.75)	90.03 (3.68)	93.28 (4.06)	90.03 (3.68)	93.28 (4.06)	-0.06 (0.31)	0.03 (0.4)	15.94 (2.52)	18.4 (6.76)
17	17	15	17.29 (0.22)	17.49 (0.33)	162.35 (4.96)	177.6 (7.61)	60.5 (7.95)	68.27 (9.59)	88.47 (3.45)	95.72 (5.1)	88.47 (3.45)	95.72 (5.1)	-0.06 (0.24)	0.1 (0.28)	14.35 (1.69)	14.87 (2.23)
18	14	12	18.46 (0.28)	18.32 (0.26)	163.96 (6.24)	179.58 (5.81)	56.5 (9.33)	72.67 (5.94)	87.93 (4.21)	96.88 (3.67)	87.93 (4.21)	96.88 (3.67)	0 (0.0)	0.08 (0.29)	14.43 (2.28)	15.08 (2.97)

*Frequency of Male and Female in each age group. Mean (standard deviation) for each of age, height, weight, (L)&(R) leg length, leg length difference, step count, by age and gender

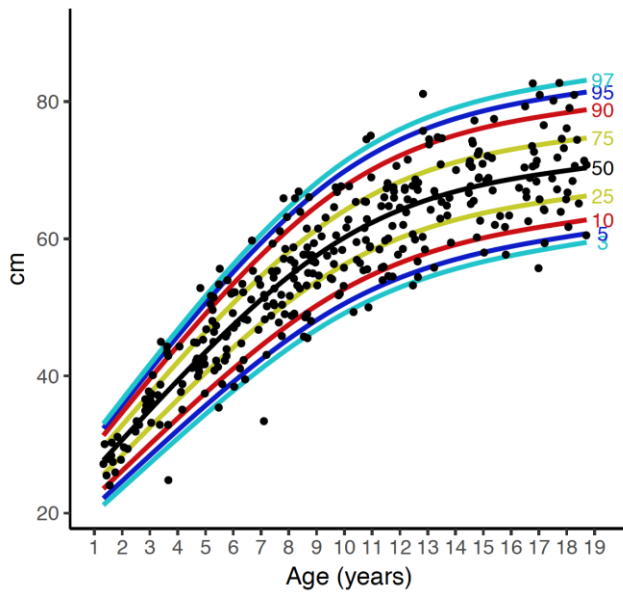
1a Velocity – male



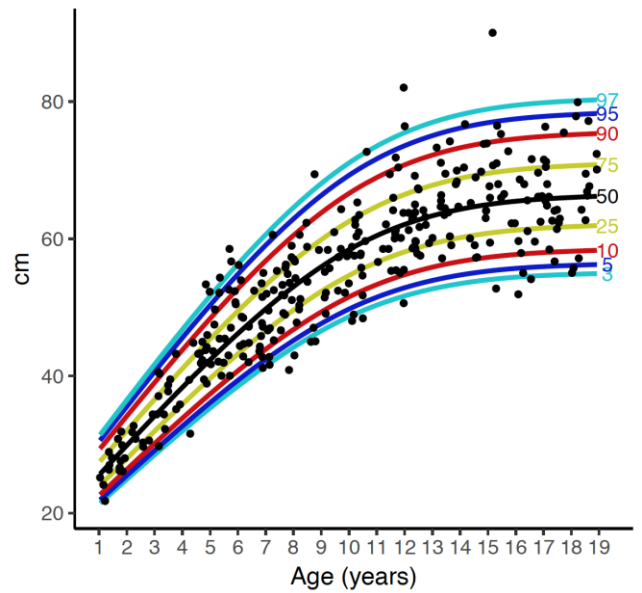
Velocity – female



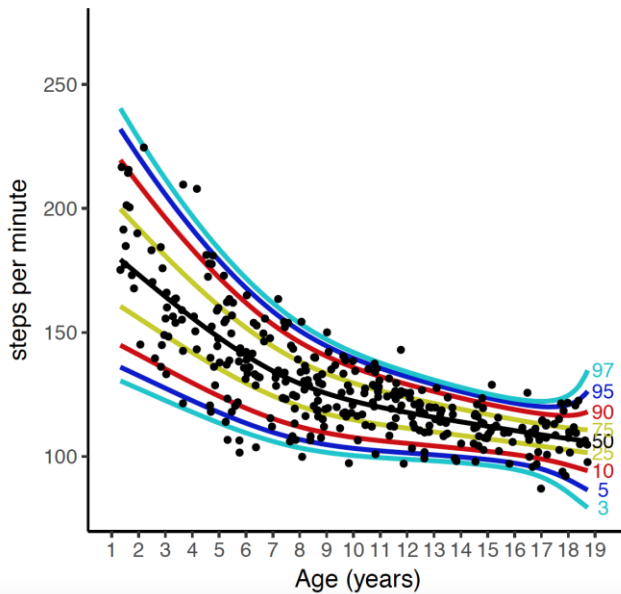
1b StepLength – male



StepLength – female



1c Cadence – male



Cadence – female

