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ORIGINAL ARTICLE

Developmental pathways of cardiorespiratory fitness from 6 to 15 years of age

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Abstract
Most of the information gathered about physical fitness of paediatric populations are cross-sectional, resulting in normative perspectives that account for average values relative to age, but not to a comprehensive understanding of developmental individual trajectories. The aim of this study was to model the longitudinal development of cardiorespiratory fitness of boys and girls from 6 to 15 years of age, using an individual centred approach. Two hundred twenty-nine school children (128 boys; 101 girls) were followed on their 20 metres shuttle run test (20mSRT) results from 6 to 15 years of age. Annual measurements were made during the four years of primary school, and again at grade 9th or 10th. Individual trajectories of 20mSRT development were modelled and grouped according to their similarities of change in three different developmental pathways that were included in subsequent hierarchical nested models for testing each sex developmental model of cardiorespiratory fitness. Final models including the developmental pathways showed better deviance statistics ($p < .001$). Interindividual slope variances were almost zero, and statistically non-significant (0.05 boys 0.01 girls; $p > .50$), meaning these models capture well the existing variability, in respect to the rate of change. Individual pathways of change in the performance of 20mSRT test can be detected in childhood and adolescence. Additionally, all individual's developmental trajectories in 20mSRT can be described using three significantly different slopes. These pathways are indicative of a high, average, or low rate of change in performance over the years and differ from the normative approach.

Keywords: 20-m shuttle run, children, adolescents, longitudinal, physical fitness

Highlights

- Individual pathways of change in the performance of 20mSRT test can be detected in childhood and adolescence.
- Individual pathways are indicative of a high, average, or low change in performance over the years, explaining the differences in performance at adolescence.
- The use of the 20mSRT percentile norms to evaluate children should be used with caution given that not always coincide with the found Individual pathways of change.
- The reasons why children and adolescents show these different developmental pathways are still to be understood.

Introduction

In childhood and adolescence, the maintenance of satisfactory cardiorespiratory fitness (CRF) levels is related with the prevention of cardiovascular disease (Ortega, Ruiz, Castillo, & Sjostrom, 2008) diabetes and obesity (Dwyer et al., 2009). A recent systematic review with meta-analysis on this thematic revealed that school-based intervention has a positive effect in promoting CRF (Minatto, Barbosa Filho, Berria, & Petroski, 2016). In adult life, it has been reported that subjects with low CRF had 70% higher risk of all cause-mortality and a 56% higher risk of mortality associated to cardiovascular disease (Kaminsky et al., 2013). In fact, the inclusion of CRF in the traditional cardiovascular disease risk score is currently being evaluated (Goff DC et al., 2014).

The multistage 20-meter shuttle run test (20mSRT), also known as beep test or PACER, is undoubtedly the most used test to estimate cardiorespiratory fitness. Initially developed by Leger,

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Lambert, Goulet, Rowan, and Dinelle (1984), it was included in the most important fitness test batteries like Fitnessgram (Research CIfA, 1987), APPHERD (American Alliance for Health PE, Recreation and Dance, 1980), Eurofit (Kemper & Mechelen, 1996), etc. Multistage 20-meter shuttle run test outputs can be interpreted under a health-related approach or using normative referenced results. All published 20mSRT results that reported normative or average values showed an expected developmental increase on performance (number of laps) associated with age, although more so for boys than girls (Bai, Saint-Maurice, & Welk, 2017; Ortega et al., 2011; Tomkinson, Carver et al., 2017).

Recently, Tomkinson, Lang et al. (2017) published the international normative values of the 20mSRT regarding 1,142,026 children from 9-to-17 years of age, representing 50 different countries from all continents. But because data used for establishing the normative values were cross-sectional, no real developmental trajectories accounting for within-participant changes in time were addressed. Cross-sectional studies have been used to estimate the association between CRF and metabolic risk in children (Buchan, Knox, Jones, Tomkinson, & Baker, 2019; Martins et al., 2010), and with mortality risks (e.g. risk of heart failure) in adults (Edwards & Loprinzi, 2016; Imboden et al., 2018), giving the possibility to understand at each moment what is the individual risk.

Longitudinal studies have reported that boys' CRF is expected to increase with age, while in girls significantly increased from 11 to 13 years and subsequently stayed constant with no decrease into adulthood (Welsman, Armstrong, Nevill, Winter, & Kirby, 1996), with CRF in late adolescence being associated with myocardial infarction later in life (Hogstrom, Nordstrom, & Nordstrom, 2014). The question is whether all subjects have the same developmental trajectories. Therefore, the possibility to predict the future risk, especially in paediatric years, will probably be more accurate if previous longitudinal information of the children can be matched with the expected longitudinal trajectories of the population. Identification of typical developmental pathways, groups of individuals with similar developmental patterns on aerobic fitness, can help to find preventive strategies for future interventions (Kwon, Janz, Letuchy, Burns, & Levy, 2015; Valla, Birkeland, Hofoss, & Slinning, 2017), and certainly will be very helpful from a clinical and training perspective.

For the best of our knowledge, longitudinal results that consider individual developmental trajectories (within-participant) on the 20mSRT test and related CRF were never addressed until now. The purposes of this study were to longitudinally model CRF development (using 20MSRT test results) from 6 to 15 years of age, on girls and boys, accounting for the possible inclusion of diverse developmental pathways. The hypotheses to be tested were (1) that not all children depicted similar developmental trajectories of 20mSRT; (2) that children could be clustered in groups according to these developmental trajectories of 20mSRT.

Materials and methods

Study design and sample

A total of 229 children (128 boys; 101 girls) were followed from 6 to 9 years and retested at 15 years of age. The initial pool of participants (621 schoolchildren) were originally recruited from fifteen primary public schools that participated in the EMVC (*Estudo Morfofuncional da Criança Vianense*), a longitudinal growth study that took part at Viana do Castelo (northern Portugal). Measurements were made annually during the four years of primary school, and again at grade 9th or 10th. The five-year time interval between the last two assessments was scheduled to intentionally avoid the individual variability effect that is typical during puberty (Malina, Bouchard, & Bar-Or, 2004). For the present study, all participants with valid data on the final moment and at least three-time point assessments were selected, resulting in 229 participants representing 37% of the initial EMCV recruited participant sample.

This study was approved by the Scientific Council of the Polytechnic Institute of Viana do Castelo. School directors approved the study, parents gave their informed consent, and children accent. Data from the first four assessments were collected at the Human Movement Laboratory of Viana do Castelo Polytechnic Institute, from April to May. The fifth assessment was conducted during Physical Education classes at eight Secondary Schools, from April to May.

Data collection

This study uses a part of a larger collection of somatic, physical fitness, and motor competence database from the EMCV longitudinal study (see Rodrigues, Leitao, & Lopes, 2012 for description)

A team of four trained observers was responsible for the assessment of the 20mSRT test. One of the observers was the same across all the time point assessments and was responsible for maintaining the procedures across all testing moments. Participants took the test in groups of four at a time. The 20mSRT test is a widely used progressive test where participants run back and forth at a specified pace from two lines 20 metres apart. The pace is externally regulated by an auditory sign (beep) that marks the moment when the participant should be at each end of the course (lap). Pace is incremented every minute and the participant remains on the test until can no longer keep up with the pace at the end of two consecutive laps. Participants were encouraged to achieve their maximal performance and when they did not, according to the observer's judgment (e.g. when showing lack of motivation to complete the task, stopping due to injury or pain; or not showing facial flushing, sweating, hyperpnoea, or unsteady gait), the result was not included in the database. The number of completed laps is the result of the test. For children aged less than 10 years of age, and to assure fully participation and motivation on the 20mSRT test, one of the trained observers ran alongside them for pacing the rhythm and giving proper encouragement. No adverse effects in the conduct of the test were found.

Statistical analyses

To understand the possible effect of using individual developmental pathways to explain changes in CRF (20mSRT) from 6 to 15 years of age, three different hierarchical nested models were tested for each sex. HLM 6.0 software was used in the analyses since it accounts for the use of unequal time intervals (i.e. in this case 0, 1, 2, 3, and 9), and allows for modelling of fixed (average effect on the baseline and slopes for each level variable), and random effects (individual variance in baseline, and in slope). Given the characteristics of the unequal time interval between assessments, only a linear approach was taken to model the data. Within the framework of the multilevel analysis, maximum likelihood estimation procedures were used. For a better interpretation of the change parameters in the model, the time metric was centred at baseline, i.e. the first moment (time 0) corresponding to the age at the first-grade assessment (6 years of age), and the temporal metric of X-axis was set to 0, 1, 2, 3, and 9, corresponding to 6, 7, 8, 9, and 15 years of age of the participants.

In the first step, the Null Model ($20mSRT = \beta 0 + R0 + E$) was used to inspect for the overall average and random error of 20mSRT across the sample, by sex.

Model 1 modelled the effect of Time (level-1) in the repeated measures of 20mSRT for each sex. To investigate for inter-individual differences on the rate of changes of 20mSRT (slopes), the estimation of the variance component of the true individual trajectories of 20mSRT over time was included in the model ($20mSRT = \beta00 + \beta10^{*}TIME + R0 + R1^{*}TIME + E$). In model 1 and 2, Time was included using a metric centred on the baseline for better interpretation of the change in 20mSRT performance over the years.

In model 2, it was formally tested the hypothesis that not all children showed similar positive rates of change in 20mSRT, i.e. that different groups of children depicting similar behaviour in their developmental trajectories of 20mSRT can be identified. Inclusion of these groups in the model was preceded by an analysis to identify them. This type of analysis, grounded in a developmental pathway's approach (Valla et al., 2017), can rely on different methods of group identification (Kwon et al., 2015; Lopes et al., 2020; Rodrigues, Stodden, & Lopes, 2016). In this study, the individual's ordinary least square (OLS) regressions from Model 1 were used to estimate each child's linear regression equation for the number of laps in 20mSRT. Slope values (β coefficients) represent annual child's rate of change (i.e. a slope of 10 denotes that an annual average increase of 10 laps is to be expected for that child). These individual's slopes representation shows an evident normal shape distribution (Figure 1) for the two sex groups, suggesting that children in the extreme values of the distribution have different annual rates of change in 20mSRT than the ones in the middle.

Assumptions of homoscedasticity and normality of level-1 and level-2 residuals were checked for all models. A non-linear model (quadratic) was also tested and compared with model 1, but a less parsimonious result and the difficulty on interpretation of the data fit (deviance 3016 vs. 3041 for girls; 4231 vs. 4249 for boys) led us to opt for the linear model. A quadratic model was further tested on model 2, but the quadratic coefficient turn to be non-significant ($p < .005$) and so we discard it from the analysis.

Accordingly, these individual slope values were clustered into three groups, representing distinct developmental pathways by sex: Low Rate of Change (Low RC: children with a rate of change below the 25th percentile for all the group); Average Rate of Change (Average RC: between the 25th and 75th percentile); and High Rate of Change (High RC: above the 75th percentile) (see Figure 2).

In consequence of this preliminary analysis, Model 2 added the individual belonging to the rate of change groups, to the previous model. Two dummy variables (Low RC, and High RC) were added to the model to

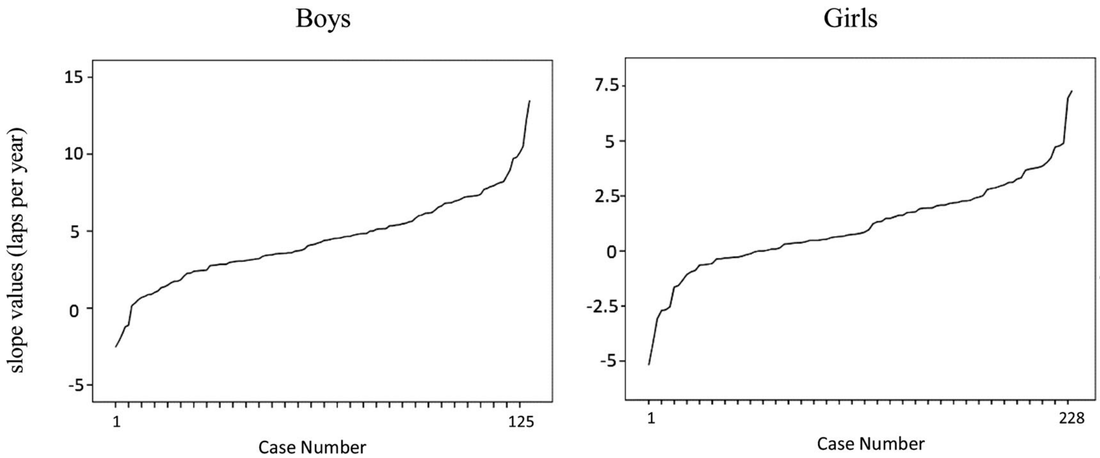

Figure 1. Distribution of slope values for boys and girls.

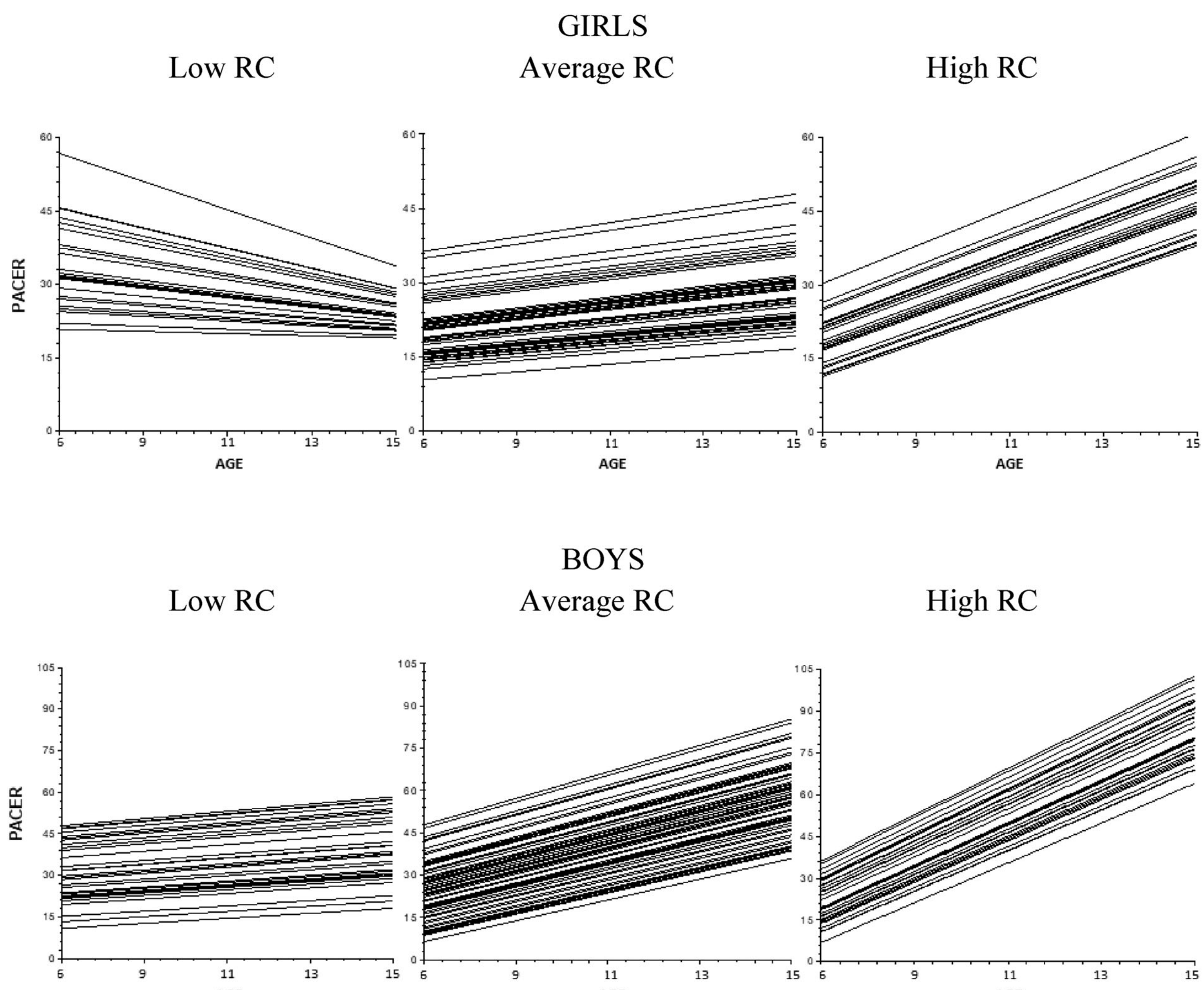

Figure 2. Representation of all individual slope values (number of laps) for each rate of change group, by sex.

address the effects on the baseline and slope values (20mSRT = β00 + β01 * LOW_RC + β02 * HIGH_RC + β10*TIME + β11 * LOW_RC * TIME + β12 * HIGH_RC * TIME + R0 + R1 * TIME + E).

Deviance statistics changes relative to the number of parameters added for each subsequent model were used for comparing the fit of the nested models.

Results

Null model examination

In the (Null) Model 0, it was determined the overall mean for both boys (39.21; $p < .001$), and girls (26.78; $p < .001$) across all moments in time. The non-explained variance of the model was bigger for boys than girls (see variance components in Table I), resulting on a better model fit for girls as assessed by the smaller deviance statistic value (3107.85 vs. 4649.82).

Model 1 examination

In Model 1, repeated measures of 20mSRT were included in the modelling (Time). As a result, both average baseline values (24.60 laps for boys; 23.28 for girls), and average slope (annual rate of change) values (3.78 laps per year for boys; 0.98 for girls) were determined. All these coefficients proved to be statistical significant (all $p < .001$) for the respective model, and the improvement in the Deviance statistics (all $p < .001$) showed that these two models generated a better fit to the data. The variance component for the Slope(s) (3.07, $p < .001$; and 1.62, $p < .001$, respectively for boys and girls) show that still exists a significant non-explained variability in the Slope coefficient of the models, i.e. the entire variability of developmental trajectories of change in 20mSRT is not yet well described by this model.

Model 2 examination

Model 2 included the effect of the subjects group clustering according to their individual rate of change, as explained in the statistics section. Deviance statistics showed that both boys' and girls' models provided a better fit for the data ($p < .001$) than the previous M1. For boys, results only showed a significant effect for the Average (Overall) baseline lap's values (25.12, $p < .001$), and not for any of the other two groups (Low RC or High RC), meaning there was no differences in the 20mSRT initial value for these three groups. For girls, Average or Low RC children showed a significantly different initial expected value for the number of laps (20.02 and 14.18, $p < .001$, respectively).

Table I. Model examination (coefficients and goodness of fit) of the three hierarchical nested models tested in boys and girls.

	Boys			Girls		
	Null model	Model 1	Model 2	Null model	Model 1	Model 2
Regression coefficients (fixed effects)						
Baseline β0						
Overall (average change) β00	39.21 (1.12)**	24.60 (1.09)**	25.12 (1.52)**	26.78 (0.82)**	23.28 (1.06)**	20.02 (1.05)**
Low rate of change, β01			5.32 (2.70)			14.18 (2.43)**
High rate of change, β02			−3.77 (2.40)			−1.18 (1.87)
Slope						
Time (average change), β10		3.78 (0.21)**	3.67 (0.10)**		0.98 (0.17)**	0.93 (0.09)**
Low rate of change, β11			−2.68 (0.24)**			−2.00 (0.24)**
High rate of change, β12			3.17 (0.24)**			2.23 (0.23)**
Variance components (random effects)						
Baseline, R0	77.91*	96.50**	109.19**	44.18**	77.06**	48.88*
Time slope, R1		3.07**	0.05		1.62**	0.01
Residual, E	332.06	99.51	81.66	95.32	59.73	50.65
Model summary						
Deviance	4649.82	4249.99	4078.17	3107.85	3041.73	2899.15
Number of estimated parameters	3	6	10	3	6	10
Statistics		M0–M1 $p < .001$	M1–M2 $p < .001$		M0–M1 $p < .000$	M1–M2 $p < .000$

Note: Model 2 estimation includes two dummy variables (0 or 1) relative to the low and the high change groups. The coefficient for each group results from the sum of the overall (or average change) parameter with the respective coefficient (ex: the baseline value for the LC group is 25.12 + 5.32 = 30.43; $^{*}p < .05$; $^{**}p < .001$).

Significant differences in the rate of change (slopes) for all groups, in both boys and girls, were found (see slope coefficients in Table I). More importantly, the interindividual slope variance became almost zero and statistically non-significant (0.05 and 0.01, respectively for boys and girls; both $p > .50$), meaning that, in respect to the slope modelling, M2 could capture most of the existing variability. All individual's developmental trajectories of change in 20mSRT are best described in this model, by three significantly different slopes.

Discussion

The identification of similar trajectories of change in developmental characteristics can be useful to signal children at risk (screening), but also to foster the understanding of the underlying mechanisms of these typical developmental pathways (Rodrigues et al., 2016; Valla et al., 2017). Individual developmental trajectories (within-participant) were never addressed for describing or explaining the performance in the 20mSRT test, and related CRF. The main purpose in this study was to understand how the possible inclusion of these diverse developmental pathways could be useful for a better understanding of the CRF development (using 20MSRT test results) from 6 to 15 years of age. In our results, it was found that using three groups representing three different clusters of rates of change (Low RC, Average RC, and High RC) allowed to significantly benefit the model interpretation for the longitudinal development of 20MSR, as discussed below.

Normative approach

Results from model 1, which models the average behaviour of 20mSRT development on boys and girls from 6 to 15 years of age, show that the average boy is expected to run 24.60 laps [95%CI = 22.46–26.74] at the age of 6, and to increase about 3.78 laps per year [95%CI = 3.39–4.17] up to the age of 15. For girls, the initial expected value was 23.28 laps [95%CI = 21.20–25.36] with an annual increase of 0.98 laps [95%CI = 0.65–1.31]. These average values of baseline and change for boys are similar to the 60th percentile, and that of girls to the 50th percentile values of the international normative 20 m shuttle run (from 9 to 15 years of age) (Tomkinson, Carver et al., 2017).

But the non-explained variance of both models 1's (see variance component in Table I), detects that a significant amount of this non-explained variance is attributable to baseline values (96.50 for boys; 77.06 for girls), and, more importantly to this study, there is still a significant unexplained variance relative to the slope (rate of change). This suggests that trajectories of change over time for 20mSRT are not parallel, and so, not all children behave according to the suggested average increasing performance over time. In fact, this seems to be the problem when a normative/average approach is taken to analyse longitudinal results, not considering the individual variability and reducing everything to a mean and a group variability (Nesselroade, 1991).

Developmental pathways approach

To try to capture these different developmental trajectories, three different conditions regarding the individual rate of change, were included in Model 2. Boys' results suggest that the rate of change (groups) of the children, do not allow to differentiate between them at baseline (baseline coefficients for the Low RC and for the High RC groups were not significant). Nonetheless, the amount of non-explained variance for the baseline estimation remained highly significant (109.19; $p < .001$) suggesting that the estimation of 25.12 laps as initial (6 years) value of 20mSRT does not represent well all the sample variability. For girls, adding the rate of change group information resulted on a better modelling of the baseline values with a 37% increment on explained variance (M1 = 77.06; M2 = 48.88). Girls with High and Average Rate of Change showed no differences on baseline values, but girls with LRC trajectories performed significantly different at the age of 6, running more 14.18 laps [95%CI = 9.5–18.9], on average. This is important because it suggests that for girls, a higher performance around the age of 6 cannot always be expected to track along childhood and adolescence. Further investigations into these observations must be conducted to better understand the relevancy of the findings, namely using other correlated variables that could help on its interpretation. As it is, this information can be used by health educators and sport's coaches to frame their analysis on the SRT20m testing of young girls, and on developmental expectations of their aerobic performance.

Along developmental time, children belonging to the Low RC group changed significantly less than the Average RC children, and these less than the High RC group. For boys, all the changes were positive (Low RC = 0.99; Average RC = 3.67; High RC = 6.84 laps per year), but for girls, changes proved to be small and even negative for one group (Low RC = −1.070; Average RC = 0.93; High RC = 3.16 laps per year). For both boys and girls, the inclusion of these three types of developmental trajectories' groups in the model allowed to detect most of the variance related to different slopes (or developmental trajectories), as denoted by the non-statistical significance of the variance component associated to inter-slope variability (see Table I). Thus, model 2 shows that we can expect children to have one of three types of change in 20mSRT performance over childhood and adolescence, a Low RC, an Average RC, or a High RC. Adolescents on the High RC group proved to be significantly better at 20mSRT performance than their peers. Univariate post-hoc analysis showed that at the age of 15, High RC boys were expected to run more 25.7 laps (95% CI = 18.3–33.4) than Average RC boys; and 44 more laps (95%CI = 35.3–52.4) than the Low RC. Girls showed similar results, with the High RC girls performing more 18.9 laps (95%CI = 13.6–24.3) than Average RC peers; and more 22.8 (16.6–28.9) than their Low RC colleagues. But this distinction between the developmental pathway groups' performance did not happen for any of the previous four moments of assessment (6, 7, 8, and 9 years of age), meaning that childhood annual values per se cannot be indicative of 20mSRT and related cardiorespiratory fitness future outcomes at adolescence.

This is important because, intuitively, children's performance in 20mSRT is expected to track into normative percentile channels along developmental years, meaning that normative values at an early age are used to predict future outcomes. This study shows that we can distinguish children that homogeneously track in groups of developmental pathways, and this distinction may be made at an early age if more than one moment in time is available. Values at an early age were not consistently related to the final values but since three general linear behaviours are described for the longitudinal change in 20mSRT, predicting a possible future outcome can be performed depending on what group of change (Low RC, Average RC, or High RC) the children belong.

Normative channels versus developmental pathways

In general, research using 20mSRT to estimate CRF development tends to show that boys improve their performance from 11 to 15 years of age, but girls do not (Baquet, Twisk, Kemper, Van Praagh, & Berthoin, 2006).which can be related to BMI developmental patterns in girls (Bonney, Ferguson, & Smits-Engelsman, 2018). Our models show similar result when only accounting for the average boy and girl, but also show that another two types of developmental pathways: the ones with a small positive or even negative trend, and the ones that change faster over the years. Girls with Low RC from 6 to 15 years not only do not improve their 20mSRT performance, but even tend to decrease, putting themselves at risk for a healthy adulthood (Martins et al., 2009). This fact maybe related to the body mass increase that in girls is due mainly by the increase of body fat (Bonney et al., 2018). This means that caution should be exerted when using a purely normative approach to classify or to predict the 20mSRT behaviour in childhood.

Limitations

This study focused only on the 20mSRT performance along childhood and adolescent years. Other characteristics (e.g. socioeconomic, educational, familiar, etc.) and variables (e.g. physical activity, motor competence, somatic status, etc.) that can account for the 20mSRT changes over the years were not included. Given that the study included puberty age range, maturational effects are to be expected that could confound the analysis on developmental trajectories during this period. Hence the option for not including any data collection during puberty years (10–15 years of age), but since no effective maturational assessment was carried out it is not possible to say that all children had completed their growth spurt at the final assessment moment.

Nevertheless, it is important to be aware that the described linear trajectories are an inference of the data collection design. Although the HLM statistical software can robustly deal with unequal data point collection, the use of one final data point at 15 years can constitute a limitation on the trajectory inference at the individual level, and so, more longitudinal data will be needed to validate our conclusions. Probably, if data points were to be annually collected throughout the 9-year period, different trajectories' shapes (e.g. curvilinear) could emerge. But this limitation does not impair the conclusion that children show different developmental patterns of CRF development as measured by 20mSRT, from 6 to 15 years of age.

Despite these limitations, we choose to model only the 20mSRT outcomes over the years because, for practical purposes, this is the information most used (and needed) in sports and educational settings.

The follow up of these subjects into adult life would be interesting and would allow to see if the developmental pathways found in this study track into adulthood years. Also still need to understand why children and adolescents show these different developmental pathways. If the scientific community could be more aware of the variables that can explain it (socioeconomic, biological, educational, etc.), it would be more capable of influencing individual behaviour and optimizing health gains. Furthermore, there is still a need to be able to predict in advance what type of developmental pathway each child will take, and for that, we need to understand what variables can be useful as predictors, and at what age.

Conclusions

In conclusion, our study shows that individual pathways of change in the performance of 20mSRT test can be detected in childhood and adolescence. These pathways are indicative of a high, average, or low change in performance over the years, explaining these differences in performance at adolescence, and differ from the normative approach, so we suggest caution should be used when the 20mSRT performance is analysed using percentile norms.

Disclosure statement

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