Physical education and sport through the centuries
2025, 12(1), 17-31
ISSN 2335-0598

Original research article DOI: 10.5937/spes2501017A

INVESTIGATING THE RELATIONSHIP BETWEEN CARDIAC AUTONOMIC MODULATION AND RESTING HEART RATE IN YOUTH ACROSS PHYSICAL ACTIVITY LEVELS

Belkadi Adel[1], Asli Houcine[2], Cherara Lalia[1-3], Benhammou Saddek[1-3], Mokrani Djemal[1-3], Sebbane Mohamed[1-3]

[1]Laboratory of Applied Sciences to Human Movement, Institute of Physical Education and Sport, University of Mostaganem, Algeria
[2]Laboratory of Physical Activity and Children Sports, Mohamed Boudiaf University of Sciences and Technology, Algeria
[3]Laboratory for Optimizing Research Programmes on Physical and Sports Activities Institute of Physical Education and Sports, University of Mostaganem, Algeria

ABSTRACT

Objective: This study aimed to explore the relationship between cardiac autonomic modulation (CAM), assessed via heart rate variability (HRV) indices (e.g., RMSSD, SDNN, SD1, SD2), and resting heart rate (HRR) in children and adolescents, focusing on how physical activity levels influence autonomic regulation and cardiovascular health.

Methods: A total of 134 children and adolescents participated. CAM and HRR were assessed using Polar heart rate monitors, and physical activity levels were evaluated with the Rider questionnaire. The relationship between CAM and HRR, stratified by physical activity levels, was analysed using linear regression adjusted for sex, age, and somatic maturation.

Results: Insufficiently active individuals showed a significant inverse relationship between high HRR and lower HRV indices, System: including root mean square of successive differences (RMSSD; β=-0.125), standard deviation of normal R-R intervals (SDNN; β=-0.142), Poincaré short-term variability (SD1; β=-0.176), and long-term variability (SD2; β=-0.114). Physically active individuals had a weaker relationship, with only the SD1/SD2 ratio (β=-0.006) significantly associated with HRR, suggesting physical activity preserves autonomic balance.

Conclusions: High HRR is linked to reduced CAM in insufficiently active youth, while physical activity mitigates this effect. Promoting physical activity enhances CAM and reduces cardiovascular risk in youth.

Key words: Heart rate variability, Cardiovascular health, Pediatric exercise, RMSSD, SDNN

Corresponding author
Belkadi Adel
adel.belkadi@gmail.com

INTRODUCTION

Cardiac autonomic modulation CAM, a critical component of cardiovascular health, reflects the balance between the sympathetic and parasympathetic branches of the autonomic nervous system (Brisinda et al., 2024a). This balance is essential for maintaining optimal heart function and adaptability to physiological demands. Heart rate variability (HRV), a non-invasive measure of CAM, has emerged as a valuable tool for assessing autonomic regulation and predicting cardiovascular risk (Carrillo et al., 2023). In recent years, the relationship between physical activity and CAM has garnered significant attention, particularly in paediatric populations, where early interventions can have long-term health benefits (Carson et al., 2017) . Changes in HRV are indeed associated with various health outcomes, particularly the risk of lethal cardiac events (Turcu et al., 2023). HRV serves as a crucial indicator of autonomic nervous system function and cardiovascular health, with both increased and decreased HRV linked to different health implications (Lee et al., 2020). Understanding HRV is crucial for assessing cardiovascular health, particularly in young individuals who may not show overt symptoms of heart disease. A study found that lower HRV indices correlate with increased cardiovascular risk, even in healthy young adults, suggesting that HRV can serve as a risk factor for future heart disease (Benhammou et al., 2025; Ramamurthy et al., 2023). Studies indicate that heightened sympathetic activity leads to decreased HRV, suggesting a dominance of sympathetic modulation during stress responses (Kim et al., 2024). HRV serves as a surrogate for assessing sympathetic nervous system (ANS) responsiveness, with pharmacological studies showing that sympathetic blockade consistently reduces HRV metrics (Maki et al., 2024).

In general, CAM is assessed through HRV, which reflects the interplay between sympathetic and parasympathetic systems (Brisinda et al., 2024a). A healthy CAM profile typically shows higher parasympathetic activity, which is linked to better cardiovascular outcomes (Brisinda et al., 2024b).High levels of chronic sympathetic activation (high HRR) and low parasympathetic activity (low CAM) are significant contributors to the onset of chronic diseases, particularly cardiovascular conditions. This imbalance can be mitigated through physical exercise, which serves as an effective non-pharmacological intervention to enhance autonomic function and promote health (Carnagarin et al., 2019). A study indicated that higher energy expenditure from physical training correlates with improved autonomic function, suggesting that exercise intensity and duration are crucial for health benefits.

The effectiveness of sports training on CAM in children has been explored through various studies, highlighting its potential benefits. A study found that sports practice in childhood significantly improved indices such as standard deviation of normal R-R intervals (SDNN) and root mean square of successive differences (RMSSD), which are indicators of HRV and autonomic function (Christofaro et al., 2024), Another study demonstrated that both physical exercise and an integrated sports and medicine intervention significantly increased HRV indices like SDNN and RMSSD in children, suggesting that structured physical activity can enhance autonomic function (Belkadi et al., 2015; Wang et al., 2024).

Regular physical training has been shown to enhance parasympathetic activity, as evidenced by increased high-frequency (HF) indices and root mean square of successive differences (RMSSD) in HRV measurements (El-Malahi et al., 2024; Urbanek et al., 2024; Moussa et al., 2025),Active individuals typically demonstrate longer R-R intervals, which are indicative of improved vagal tone and autonomic regulation (El-Malahi et al., 2024; Belkadi et al., 2025).The relationship between cardiorespiratory fitness (CRF) and cardiovascular risk factors, particularly in adolescents with varying levels of physical activity, is critical for understanding cardiovascular health (Prado et al., 2024). Adolescents with lower physical activity levels may experience higher sympathetic nervous system (SNS) activity, leading to adverse cardiovascular profiles (Nascimento et al., 2019).

There are virtually no studies on how different levels of activity influence the relationship between heart rate control and HRR in children and adolescents (Abdelkader et al., 2021; Chen et al., 2022). Data from the National Health and Nutrition Examination Survey indicates a decline in ideal cardiovascular health as adolescents age, with only 41% of older adolescents maintaining ideal health status (Baker-Smith et al., 2022; Chrara et al., 2018).

The main aim of this study was to establish whether CAM was related to cardiorespiratory fitness in children and adolescents and, more specifically, to what extent this association depended on exercise-induced differences in the amount of physical activity. We attempted to estimate the independent contributions of physical activity in an autonomous model of cardiovascular regulation while controlling for covariates such as age, sex, body mass index (BMI) and somatic maturation. This study not only fills a very important gap in the literature, but also provides a basis for future research and public health initiatives designed to use physical activity to improve cardiovascular health in paediatric populations.

Based on the existing literature, we hypothesized that: (1) insufficiently active children and adolescents would exhibit a stronger inverse relationship between high HRR and reduced HRV indices (e.g., RMSSD, SDNN, SD1, SD2) compared to their physically active peers, reflecting poorer CAM; (2) physically active individuals would demonstrate a weaker association between HRR and HRV indices, indicating a protective effect of physical activity on autonomic balance; and (3) these relationships would persist after adjusting for confounding factors such as age, sex, BMI, and somatic maturation.

METHODS

Participants

The sample consisted of 134 children and adolescents (58 females, 76 males; mean age: 9.52 ± 1.61 years, range: 7-12 years) recruited from a national project in Mostaganem catering to low-income youth. Participants had a mean BMI of 21.5 ± 5.9 kg/m^2 and a mean Peak Growth Velocity (PGV) of -4.30 ± 1.01 years from peak height velocity, indicating a pre-pubertal to early pubertal maturation status. Individuals take part in the project at times other than school hours, either in the morning or in the afternoon. The inclusion criteria for adolescents to take part in the study were: (i) being enrolled and taking part in the activities of this Project; (ii) not having any known heart disease; (iii) not using any medication to control hypertension or heart rate; and (iv) returning the Informed Consent Form duly signed by the parents or tutors, authorising the adolescent to take part in the research.

Exclusion criteria: Participants with R-R interval errors exceeding 5%. This study was approved by the Research Ethics Committee of the Institute of Physical Education and Sports (IEPS: 20052024.1.003) and conducted in accordance with the principles of inclusive education and ethical guidelines (World Medical Association, 2013). Data was collected through direct measurements and face-to-face questionnaires, individually, by previously trained teachers and coaches, in order to guarantee the reliability of the answers and reduce possible biases.

Anthropometric measurements

Body weight, height, torso-cephalic height and leg length were measured. Weight was measured using a InBody Digital Scale (Tanita BC-568, Japan), accurate to 0.1kg. Height was measured with the individual standing upright, feet together and barefoot, taking into account the height of the apex of the head. Trunk-brain height was obtained with the individual sitting on a 50 cm stool, considering the height of the apex of the head and subtracting the measurement of the stool. For both measurements, a portable stadiometer (Seca 213, Philippines) was used, accurate to 0.1cm. To check leg length, the trunk-cephalic height value was subtracted from the height value. All measurements were standardised according to Belkadi et al. (2025). The body weight and height values were used to calculate the body mass index (BMI) used both to characterise the sample and to adjust the statistical analysis.

Somatic maturation

Somatic maturation was calculated using the PGV method for adolescents, developed by Moore et al., (2015),which has been validated for accuracy in predicting maturational timing in youth (Sherar et al., 2005; Malina & Kozieł, 2014). Anthropometric measurements of weight, height, trunk-cephalic height, and leg length were used, adjusted for sex.

Level of physical activity

To assess the level of physical activity, the questionnaire (Rider et al., 2022) was applied, previously validated for children and adolescents (Solans et al., 2008). The questionnaire is divided into three dimensions: activities at school, sports activities and leisure activities. Based on these answers, the physical activity indexes were calculated for each of the dimensions and the sum of these values provided the result for the total index of physical activity practice. According to the overall physical activity index, the subjects were stratified into quartiles, with those located in the highest quartile classified as physically active - 4th quartile - and young people in the lower quartiles classified as insufficiently active.

Resting Heart Rate (HRR)

HRR was measured using a heart rate monitor (Polar FT-1, model T-31, Finland), a device validated for reliable heart rate assessment in youth (Gamelin et al., 2008). Before the assessment, all subjects remained seated for 15 minutes, with two measurements taken at a 5-minute interval, and the mean value adopted as the final result.

Cardiac Autonomic Modulation

To analyse CAM, heart rate was recorded beat by beat using a heart rate monitor (model RS800CX, Polar Electro, Finland) All measurements were standardised according (Tebar et al., 2020; Manar et al., 2023). For this assessment, the subjects lay supine for 30 minutes in a temperature-controlled environment (25°C ± 1°C).and were instructed to: (I) not ingest stimulating drinks or foods such as caffeine and chocolate and not perform strenuous exercise for 24 hours prior to the assessment; (II) fast for at least 2 hours; and (III) the girls could not be in their menstrual period.

In the series of R-R intervals obtained, digital filtering was carried out in the Polar Pro Trainer programme (version 5), followed by manual filtering in excel and 1000 R-R intervals from the most stable period of the tracing were used for analysis. This period was determined visually by a previously trained evaluator. Only the series of R-R intervals with more than 95% sinus beats were included in the study.

Kubios HRV Scientific was used to analyse the data, and HRV indices were obtained in the time and frequency domains (Tarvainen et al., 2014; Benhammou et al., 2022).

The indices analysed in the time domain were:

I - The average of the R-R intervals;

II - The average standard deviation of all the normal R-R intervals (SDNN);

III - The square root of the mean squared differences between successive R-R intervals (RMSSD). In the frequency domain, the following indices were calculated using the fast Fourier transform: High frequency (HF), with a range of 0.15 to 0.4 Hz, and low frequency (LF), with a range of 0.04 to 0.15 Hz, in normalised units, and the LF/HF ratio. In addition, the indices SD1 (standard deviation of the instantaneous beat-to-beat variation), SD2 (long-term standard deviation of the R-R intervals) and the SD1/SD2 ratio were obtained using the Poincare plot.

Statistical analysis

The Shapiro Wilk test was used to test the normality of the data. The independent t-test was used to characterise the sample according to level of physical activity.

Pearson’s correlation was used to relate HRR and CAM according to the level of physical activity. To analyse the association between CRF and CAM indices stratified by physical activity level, Linear Regression was used in an unadjusted model and adjusted for confounding factors - gender, age, BMI and PGV. The analyses were carried out using SPSS software version 15.0 All statistical analyses that resulted in $p < 0.01$ and $p < 0.05$ are considered statistically significant.

RESULTS

This study included 134 children and adolescents, 58 girls and 76 boys, with a mean age of 9.52 (± 1.61) years Table 1. The average HRR was 86.56 (± 11.35) beats per minute. Table 2 shows the characteristics of the sample according to their level of physical activity. No significant difference was observed when comparing physically active and insufficiently active individuals.

Table 1. Characterisation of the sample.

Variable	Active Mean ±SD	Insufficiently Active Mean ±SD	P-value
Age (years)	10.45 ± 0.79	9.75 ± 0.76	0.839
Weight (Kg)	46.50 ± 13.30	45.50 ± 15.00	0.754
Height (cm)	151.10 ± 9.41	152.70 ± 11.60	0.594

Table 2. characteristics of the sample according to their level of physical activity.

Variable	Active Mean ±SD	Insufficiently Active Mean ±SD	P-value
BMI (Kg/m^2)	22.50 ± 6.30	20.50 ± 5.50	0.278
PGV	-4.30 ± 0.85	-4.30 ± 1.16	0.607
Heart Rate (bpm)	90.70 ± 10.80	85.90 ± 09.20	0.264
RMSSD (ms)	58.50 ± 21.60	54.40 ± 27.80	0.505
SDNN (ms)	64.00 ± 23.20	66.60 ± 26.30	0.659
LF (n.u)	51.70 ± 14.10	49.00 ± 13.50	0.386
HF (n.u)	48.30 ± 14.10	51.00 ± 13.50	0.520
LF/HF	1.25 ± 0.78	1.15 ± 0.75	0.548
SD1 (ms)	38.50 ± 15.30	41.30 ± 19.70	0.505
SD2 (ms)	81.50 ± 30.30	84.20 ± 32.70	0.713
SD1/SD2 (ms)	0.47 ± 0.16	0.47± 0.15	0.986

SD = Standard Deviation; BMI = Body Mass Index; PGV = Peak Growth Velocity; RMSSD = Root Mean Square of the differences between adjacent normal R-R intervals in a time interval expressed in milliseconds; SDNN = Standard Deviation of all normal R-R intervals; LF = Low frequency component in standardised units; HF = High frequency component in standardised units; SD1 = Standard deviation of instantaneous beat-to-beat variability; SD2 = Standard deviation of long-term variability; ms = Milliseconds; nu = Standardised unit; Kg/m^2 = Kilograms per metre squared.

Of all the CAM indices analysed in this study, RMSSD, SDNN, SD1 and SD2 were inversely related to high HRR values in children and adolescents who were not sufficiently active. When physically active individuals were considered, the CAM indices inversely related to higher HRR values were RMSSD (p = 0.038) and SD1 (p = 0.037). This information is presented in Table 3.

Table 3. Correlation between HRR indices in insufficiently active and active children and adolescents.

Variable	Insufficiently Active		Active	
	r	P-value	r	P-value
RMSSD (ms)	-0.360	0.002	-0.415	0.035
SDNN (ms)	-0.340	0.001	-0.290	0.155
LF (n.u)	-0.110	0.340	0.310	0.125
HF (n.u)	0.110	0.340	-0.310	0.125
LF/HF	0.010	0.920	0.230	0.250
SD1 (ms)	-0.330	0.002	-0.415	0.036
SD2 (ms)	-0.340	0.002	0.240	0.240
SD1/SD2 (ms)	-0.180	0.115	-0.360	0.075

RMSSD = Root mean square of the differences between adjacent normal RR intervals over a time interval expressed in milliseconds; SDNN = Standard deviation of all normal R-R intervals; LF= Low frequency component in normalised units; HF= High frequency component in normalised units; SD1 = Standard deviation of instantaneous beat-to-beat variability; SD2 = Standard deviation of long-term variability; ms = Milliseconds; n.u = Standardised unit.

Table 4 provides information on the magnitude of the associations in the unadjusted and adjusted form, taking into account confounding factors (gender, age, BMI and PGV). In children and adolescents who were insufficiently active, an inverse relationship was observed between higher HRR values and lower HRV indices. This relationship was observed in the RMSSD and SDNN indices and in the Poincaré plot (SD1 and SD2), even after adjusting for confounding factors. In children and adolescents considered to be physically active, the inverse relationship between HRR and HRV indices, after adjustments, only occurred in the SD1/SD2 relationship.

Physical education and sport through the centuries
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ISSN 2335-0598

Table 4. Association between HRR and HRV in insufficiently active and active children and adolescents

	RESTING HEART RATE					
	Not Adjusted			**Adjusted**		
Variable	**β**	**CI (95%)**	**P-value**	**β**	**CI (95%)**	**P-value**
Insufficiently Active						
RMSSD (ms)	-0.135	-0.225; -0.045	**0.003**	-0.125	-0.215; -0.035	**0.006**
SDNN (ms)	-0.145	-0.240; -0.050	**0.002**	-0.140	-0.235; -0.045	**0.004**
LF (n.u)	-0.095	-0.285; 0.095	0.335	-0.105	-0.295; 0.085	0.300
HF (n.u)	0.095	-0.095; 0.285	0.335	0.105	-0.085; 0.295	0.300
LF/HF	0.165	-3.250; 3.580	0.920	-0.130	-3.240; 2.980	0.930
SD1 (ms)	-0.190	-0.315; -0.065	**0.003**	-0.175	-0.300; -0.050	**0.006**
SD2 (ms)	-0.115	-0.190; -0.040	**0.003**	-0.110	-0.185; -0.035	**0.004**
SD1/SD2 (ms)	-0.002	-0.004; 0.001	0.115	-0.002	-0.004; 0.001	0.200
Active						
RMSSD (ms)	-0.230	-0.440; -0.020	**0.035**	-0.205	-0.430; 0.020	0.075
SDNN (ms)	-0.150	-0.360; 0.060	0.155	-0.110	-0.340; 0.120	0.350
LF (n.u)	0.265	-0.080; 0.610	0.125	0.310	-0.040; 0.680	0.085
HF (n.u)	-0.265	-0.610; 0.080	0.125	-0.310	-0.680; 0.040	0.085
LF/HF	3.550	-2.660; 9.760	0.245	4.050	-2.950; 10.900	0.225
SD1 (ms)	-0.320	-0.620; -0.020	**0.035**	-0.280	-0.600; 0.040	0.075
SD2 (ms)	-0.095	-0.255; 0.065	0.235	**-0.060**	-0.240; 0.020	0.505
SD1/SD2 (ms)	-0.004	-0.009; 0.000	0.070	**-0.006**	-0.010; -0.001	**0.030**

Adjusted for sex, age, PGV and BMI; CI = Confidence interval; RMSSD = Root mean square of the differences between adjacent normal RR intervals over a time interval expressed in milliseconds; SDNN = Standard deviation of all normal R-R intervals; LF= Low frequency component in normalised units; HF= High frequency component in normalised units; SD1 = Standard deviation of instantaneous beat-to-beat variability; SD2 = Standard deviation of long-term variability; ms = Milliseconds; nu = Normalised unit.

DISCUSSION

In the present study, an inverse relationship was observed between high HRR and the RMSSD, SDNN, SD1 and SD2 indices in insufficiently active individuals. However, in physically active individuals, this relationship was only observed for the SD1/SD2 index, suggesting that physical activity may play a protective role in improving CAM at younger ages, thereby reducing cardiorespiratory fitness.

In physically active individuals, only the SD1/SD2 ratio was associated with the HRR of children and adolescents in the adjusted analysis. This indicates that sufficient physical activity levels may enhance CAM, independent of age, gender, BMI, or somatic maturation PGV. These findings align with previous research by (Adel et al., 2019; Christofaro et al., 2024; Murakami et al., 2025), which demonstrated that higher physical activity levels are associated with increased HRV and reduced HRR in healthy adults. Similarly, Silva et al (2017) found that high HRR was linked to reduced parasympathetic activity and overall CAM in individuals with type 1 diabetes. The relationship between HRR and CAM appears to be more pronounced in insufficiently active individuals, as evidenced by both unadjusted and adjusted analyses (Carrillo et al., 2023; Ishida & Okada, 2001; Tebar et al., 2020). Insufficiently active children and adolescents exhibited lower parasympathetic activity, likely due to a lack of regular physical exercise (Belkadi et al., 2020; Chen et al., 2022). This reduced CAM increases the risk of cardiovascular diseases, as the heart’s ability to respond to stress is compromised (Engler & Engler, 1995; Kivimäki & Steptoe, 2018). Further supporting these findings, Ilic et al (2024) observed higher systolic and diastolic blood pressure and lower CAM in obese individuals compared to those with normal weight (Adel et al., 2019; Beboucha et al., 2021). This may be attributed to increased ANS activity in obese individuals, potentially driven by metabolic changes and autonomic dysfunction associated with obesity (Greenfield & Campbell, 2008; Belkadi et al., 2025). Additionally, prior research has identified a positive correlation between HRR and BMI.

In a systematic review, (Silva et al., 2017; Benhammou et al., 2024) examined the effects of physical exercise on CAM in healthy pediatric populations. While only two trials were included, no significant differences were found between intervention and control groups (Hejazi & Ferrari, 2022). Conversely, Sandercock et al. (2008) stratified their sample by physical activity levels and found that the most active individuals had significantly higher R-R intervals, SDNN, and RMSSD values compared to their less active counterparts. These improvements are likely due to cardiovascular adaptations resulting from regular and systematic exercise, which independently influence cardiac autonomic regulation (Kim Choun, 2020; Benhammou et al., 2022).

The originality and strengths of this study lie in its exploration of the relationship between HRR and CAM in children and adolescents, stratified by physical activity levels a topic that remains underexplored in the literature. By adjusting for potential confounding factors, this study provides a more accurate estimation of the independent effects of physical activity on cardiovascular health. However, the cross-sectional design and non-randomized sampling limit the ability to infer causality and may affect the generalisability of the results. Additionally, central obesity was not analysed in this study, which could be a relevant explanatory variable for these associations, as abdominal fat is linked to sympathetic activation through neural pathways involving leptin and adipokines (Rahmouni, 2010; Santos-Magalhaes et al., 2015; Mohamed et al., 2019).

Future research should consider incorporating measures of sedentary behavior and prolonged sedentary periods, as these factors are associated with obesity in children and adolescents (Adamo et al., 2015; Boudehri et al., 2023) and are important determinants of health, independent of physical activity levels (de Rezende et al., 2014). Even individuals who meet physical activity guidelines may still spend significant time in sedentary activities, which could impact autonomic regulation.

The findings demonstrate that insufficiently active individuals exhibit a strong inverse relationship between high HRR and reduced HRV indices, such as RMSSD, SDNN, SD1, and SD2, indicating poorer CAM. In contrast, physically active children and adolescents show a weaker relationship, with only the SD1/SD2 index significantly associated with HRR (Benhammou et al., 2025). This suggests that regular physical activity enhances autonomic regulation, promoting cardiovascular health even at a young age. In conclusion, promoting physical activity from an early age is crucial for improving autonomic regulation and reducing cardiovascular risk in children and adolescents. Public health initiatives and educational programs should prioritize increasing physical activity levels in this population to foster long-term health and well-being (Yacine et al., 2020; Senouci et al., 2024). By addressing these factors, we can help prevent future health complications and ensure healthier outcomes as these individuals transition into adulthood.

CONCLUSION

This study demonstrated that high HRR is inversely associated with multiple HRV indices (RMSSD, SDNN, SD1, SD2) in insufficiently active children and adolescents, indicating reduced CAM and increased cardiovascular risk. In contrast, physically active youth exhibited a weaker relationship, with only the SD1/SD2 index significantly linked to HRR, suggesting that regular physical activity enhances autonomic balance. These findings confirm our hypotheses that physical activity mitigates the adverse effects of high HRR on CAM and underscore its protective role in youth cardiovascular health. The results directly address our aim to explore how physical activity levels influence the relationship between CAM and HRR, highlighting the need to promote exercise in pediatric populations to improve autonomic regulation and reduce future cardiovascular risk

ACKNOWLEDGMENT

We thank the Algerian Thematic Agency for Research in Social and Human Sciences (ATRSSH) for maintaining and supporting finances and quality of research. And Training-University Research Projects (PRFU).

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Received on 16.03.2025.
Accepted on 22.04.2025.