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High-Sensitivity Cardiac Troponin T Release After the 20-m Shuttle Run Test in 733 Healthy Children and Adolescents

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ABSTRACT

This study aimed to assess the effect of exercise on high-sensitivity cardiac troponin T (hs-cTnT) concentrations in children and adolescents and to examine whether sex, maturational status, anthropometric characteristics, cardiorespiratory fitness, and physical activity influence the hs-cTnT response. In this trial 733 participants completed the 20-m shuttle run test. Venous blood samples were collected at rest and 3 h postexercise to determine hs-cTnT concentrations. We included 296 girls and 437 boys (12.2 ± 1.7 years; 40% girls). At baseline, 61% of participants had hs-cTnT values below the limit of detection (LoD), and 2.5% exceeded the upper reference limit (URL). Postexercise, 36% remained below LoD, while 7.5% exceeded the URL. Overall, hs-cTnT increased from baseline to 3 h postexercise in 56.2% of participants. Linear mixed-effects models showed a significant main effect of time ($\beta = -0.42$, 95% CI 0.35–0.49; $p < 0.01$) and no main effect of sex ($p = 0.85$), although a small but significant time × sex interaction was observed ($\beta = -0.11$, 95% CI −0.20 to −0.02; $p = 0.021$), indicating a slightly greater exercise-induced increase in girls. Additional significant time × covariate interactions were identified for maturational, anthropometric, and fitness-related variables. However, these factors together explained only a small proportion of the overall variability in hs-cTnT response. Consequently, the 20-m shuttle run test induces a significant increase in hs-cTnT concentrations in children and adolescents. Exercise-induced hs-cTnT release is common but highly heterogeneous, and is only partly explained by sex, maturational, anthropometric, and fitness-related factors, suggesting an important contribution of individual-specific determinants not captured by conventional variables.

1 | Introduction

Cardiac troponins (cTn), particularly troponin T (cTnT) and troponin I (cTnI), are highly specific biomarkers of myocardial injury and have been extensively used in clinical settings to diagnose acute coronary syndromes [1]. However, recent research has demonstrated that cTn levels can transiently increase following intense physical activity, even in the absence of underlying cardiac pathology [2–4]. High-sensitivity cardiac troponin (hs-cTn) assays, particularly high-sensitivity cardiac troponin T (hs-cTnT), have replaced standard tests, enabling the detection of extremely low cTn levels in 99% of the population, with a coefficient of variation below 10%. These assays can even detect circulating cTn in at least half of the healthy individuals at rest [5]. Nevertheless, their increased sensitivity also raises the likelihood of false positives due to noncardiac causes, such as physical exercise. The mechanisms underlying this phenomenon during exercise and the clinical relevance of postexercise cTn elevations are still debated [2].

While some research suggests distinct patterns in cTn release kinetics between young populations and adults [6], other studies involving both adults and adolescents revealed no significant differences in either the magnitude or kinetics of cTn release [7, 8]. Following physical exertion, children and adolescents typically experience an elevation in cTn levels, particularly hs-cTnT concentrations, which peaks within 3–6 h postexercise before returning to baseline levels within 24 h in most cases [6, 9]. Assessing cTn release in children and adolescents after exercise is especially valuable, as the relative absence of confounding factors like cardiac disease or hypertension, common in adults, allows for a clearer interpretation of cTn levels as markers of cardiac stress or potential injury in a healthy pediatric population.

The variability among individuals in cTn release following exercise is well-documented, with some subjects exceeding the upper reference limit (URL) and others showing no or only a modest release. This has led to the proposition of "responders" and "nonresponders" to exercise-induced cTn release, yet previous studies have struggled to clearly identify the individual characteristics that contribute to this variability, such as sex, maturity, exercise volume, intensity, age, and training status [8, 10].

Most studies examining cTn release in children and adolescents have focused on athletes undergoing high-intensity, prolonged exercise tests [11]; however, limited data exist regarding cTn release in nonathletic children and adolescents who engage in mandatory physical education classes or participate in more common endurance efforts, such as the 20-m shuttle run test (20mSRT) regardless of athletic status. This gap in knowledge is particularly relevant given that the 20mSRT, a globally standardized assessment of cardiorespiratory fitness, is commonly administered to children and adolescents worldwide [12]. Therefore, research using the 20mSRT could provide valuable insights into the cTn response to exercise across a broad pediatric age range, reflecting the physical activity experiences of most youth.

While the study of exercise-induced cTn release in children and adolescents is often motivated by the increasing participation of young individuals in competitive sports and endurance training, it is equally important to evaluate nonathletic populations to gain a comprehensive understanding of cardiac responses to physical activity across different levels of fitness and activity. The increasing use of hs-cTn assays has further highlighted the need to establish age-specific reference values and clarify the clinical significance of transient hs-cTnT elevations postexercise. This study aims to assess the effect of exercise on hs-cTnT concentrations in children and adolescents aged 8–16 years, stratified by sex. Secondary objectives are to investigate whether participant characteristics such as physical activity levels, biological maturity, VO_2max and demographic factors influence the hs-cTnT response.

2 | Methods

2.1 | Participants

A total of 733 participants (40% girls and 60% boys) were included in the study. The sample was drawn from school-based sports programs and clubs in southern Catalonia and northern Valencia, covering both urban and rural areas. All participants completed the study procedures. Inclusion criteria were established to ensure a healthy pediatric and adolescent population to allow accurate analysis of cardiovascular biomarkers. Participants were included only if they met the following conditions: age between 8 and 16 years, regular engagement in organized sports (football, basketball, judo, swimming, track and field, etc.), and no personal or family history of cardiovascular disease. These criteria were assessed using the PAR-Q questionnaire [13], and a standardized cardiac health questionnaire based on the American Heart Association (AHA) guidelines, which participants completed with the assistance of two trained researchers. Participants and their legal guardians were informed of the study's objectives, procedures, potential risks, and benefits. Informed consent was obtained from both participants and guardians prior to data collection.

This research was conducted within the framework of the COR-School project, a long-term observational study focused on the heart health of students in the northeast of Spain. The study procedures have been approved by the Ethics Committee for Clinical Research of the Sports Administration of Catalonia (30/CEICGC/2020) and comply with the principles and recommendations of the latest revision of the Declaration of Helsinki [14]. The study was conducted following the STROBE guidelines [15].

2.2 | Research Design and Protocol

The research protocol was designed as a pre–post test, following methodological standards established in previous kinetic studies of hs-cTnT in exercise science [16]. Upon arrival, anthropometric assessments were conducted using a precision wall stadiometer (accuracy: 0.1 cm; Year-Sayol, Barcelona, Spain) and a medical scale (accuracy: 0.05 kg; SECA 711, Hamburg, Germany) to record height and weight, from which body mass index (BMI) was calculated [8, 17]. Pubertal status was assessed through a validated self-report questionnaire based on Tanner staging [18]. Maturational status was assessed using the Mirwald maturity offset, an estimate of biological maturity indicating how many years before or after their peak high velocity (PHV) they are, was assessed using the age, the standing height, sitting heigh, leg length and body mass [19]. To identify which participants are physically active or inactive, the Physical Activity Questionnaire (PAQ), PAQ-C for children and PAQ-A for adolescents was used. A cutoff score of 2.75 was applied, classifying individuals with scores ≥ 2.75 as active and those below as inactive [20].

The interventions were performed in the afternoon in an indoor sports hall, and all participants were asked to abstain from strenuous exercise for 48 h before the exercise test. Participants then completed a standardized 5–10-min warm-up consisting of jogging and stretching exercises prior to performing the 20mSRT [12]. The 20mSRT is a well-validated component of the ALPHA-Fitness battery [12] that assesses cardiorespiratory fitness. It requires individuals to shuttle between two lines 20 m apart at an incrementally increasing pace dictated by auditory signals, continuing until volitional exhaustion or inability to maintain the required pace [21]. Estimated VO_2max was calculated using the Léger equation [21]. Heart rate (HR) was recorded continuously using an HR monitor (Polar Team 2, Kempele, Finland) at 1's intervals. Maximal heart rate (HRmax) and relative heart rate (rHR), expressed as a percentage of HRmax (%HRmax), were derived from these recordings. Participants were instructed to perform the test at maximal possible intensity. Immediately after the test, participants reported the rating of perceived exertion (RPE) using the Borg CR10 scale to confirm that the effort performed was of high intensity. During the 3 h recovery period, participants were instructed to refrain from any physical activity that could affect hs-cTnT levels.

2.3 | Blood Sampling and Analysis

Before the 20mSRT, a first venous blood sample was taken. A second venous blood sample was collected exactly 3 h postexercise, a timing chosen based on evidence indicating peak postexercise hs-cTnT concentrations within this timeframe [11, 22]; notably, all hs-cTnT analyses were performed as single measurements without duplicate testing. For each sample, 5 mL of venous blood was drawn from the antecubital vein by venipuncture with participants in a seated position, performed by a certified nurse. Blood samples were immediately centrifuged at 3500 min^{-1} using a Sigma 2k-15 centrifuge (Sigma Laborzentrifugen GmbH, Germany), after which serum was aliquoted and stored at −80°C for subsequent hs-cTnT analysis. Serum hs-cTnT concentrations were determined using the Troponin T hs STAT immunoassay on a Cobas E 601 analyzer (Roche Diagnostics, Penzberg, Germany). This assay has a measuring range of 3–10 000 ng/L with a limit of detection (LoD) of 3 ng/L [23]. The intra-assay coefficient of variation at a mean hs-cTnT concentration of 13.5 ng/L was 5.2%. Prior to analyses, the analyzer was calibrated using standard calibrators according to the manufacturer's recommended protocols [24]. The URL for hs-cTnT, defined as the 99th percentile of healthy participants, was 14 ng/L.

2.4 | Statistical Analysis

Data distributions were inspected visually using density plots, and normality was assessed using the Shapiro–Wilk test. Continuous variables are presented as mean (standard deviation) [range] when normally distributed, or as median (interquartile range) [range] when skewed. Categorical variables are reported as frequencies and percentages.

Between-group differences by sex were evaluated using linear regression models (ANOVA) for continuous variables, and logistic regression for categorical variables. Ordinal logistic regression was used to analyze Tanner stage. Reference percentiles for pre- and postexercise hs-cTnT concentrations were estimated following the method described by Horn et al. [25]. Nonparametric percentiles and their 95% confidence intervals were subsequently computed using bootstrap resampling. Group differences in hs-cTnT values were further examined by comparing the proportions of participants with concentrations above the URL and below the LoD using logistic regression. In addition, log-transformed hs-cTnT concentrations and hs-cTnT delta values (post–pre) were analyzed using linear regression models to account for skewed distributions.

The effect of exercise and sex on hs-cTnT was evaluated using a linear mixed-effects model [26, 27], which extends repeated-measures ANOVA by explicitly accounting for within-participant correlation. Because hs-cTnT concentrations included zero values, an offset of 1 was added prior to log-transformation. The model included time (baseline/3 h postexercise), sex, and their interaction (time × sex) as fixed effects, along with a random intercept for participant ID to account for repeated measurements. Fixed effects were tested using ANOVA of the fitted mixed model with Type III *F*-tests and Satterthwaite-approximated degrees of freedom; categorical predictors were coded using sum-to-zero contrasts to support Type III inference. Estimated marginal means (EMMs) for hs-cTnT by time within sex and corresponding pairwise time contrasts were calculated to aid interpretation of significant effects. EMMs were back-transformed from the log scale for presentation, and Kenward–Roger degrees of freedom were used for EMM-based contrasts.

To examine covariate effects of physical activity, development, anthropometrics, and shuttle run test variables, separate linear mixed-effects models were fitted for each covariate of interest, including time, sex, the covariate, and the time × covariate interaction. In these models, the exercise response was defined as the within-participant change in hs-cTnT from baseline to 3 h postexercise (time effect). Effect modification by each covariate was evaluated using the time × covariate interaction term; continuous covariates were mean-centered for interpretability.

Model assumptions were verified using residual plots and Q–Q plots to assess normality, homoscedasticity, and the presence of influential points. Model fit was evaluated using the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC). Variance explained was summarized using marginal R^2 (fixed effects only) and conditional R^2 (fixed plus random effects). Statistical significance was set at $p < 0.05$. All analyses were conducted in R (version 4.3.2) using the packages *stats*, *lme4*, *lmerTest*, *ordinal*, *referenceIntervals*, and *performance* [28–30].

3 | Results

3.1 | Participant Characteristics

A total of 296 girls and 437 boys were included in the analysis, with a mean age of 12.2 ± 1.7 years, body weight of 47 ± 12 kg, height of 153 ± 12 cm, and estimated VO_2max of 46 ± 7 mL·kg^{-1}·min^{-1}. Descriptive statistics are presented in Table 1. According to the PAQ questionnaire results, 66% of the subjects were considered physically active, 55% of girls and 73% of boys, while remaining 34% were classified as inactive [20]. Boys

TABLE 1 | Summary of participants' characteristics.

Characteristic	Overall	Girls	Boys	Sex *p*
n	733 (100%)	296 (40%)	437 (60%)	
Physical activity				
PAQ (overall)	2.99 (0.59) [1, 5]	2.85 (0.56) [1.01, 4.65]	3.09 (0.60) [1.24, 5.00]	**< 0.001**
PAQ-C (< 14 years)	3.02 (0.59) [1.01, 5.00]	2.87 (0.55) [1.01, 4.65]	3.12 (0.59) [1.24, 5.00]	**< 0.001**
PAQ-A (> 14 years)	2.76 (0.59) [1.44, 4.17]	2.69 (0.57) [1.44, 4.11]	2.82 (0.61) [1.51, 4.17]	0.35
Development				
Age (years)	12.2 (1.7) [8.2, 16.2]	12.16 (1.67) [8.34, 16.24]	12.26 (1.64) [8.22, 16.16]	0.42
Mirwald PHV offset (years)	−2.31 (1.30) [−5.54, 2.26]	−2.21 (1.14) [−5.12, 0.36]	−2.38 (1.40) [−5.54, 2.26]	0.092
Maturational stage				0.0015
I	115 (17%)	38 (14%)	77 (19%)	
II	216 (33%)	75 (28%)	141 (36%)	
III	183 (28%)	83 (31%)	100 (25%)	
IV	128 (19%)	61 (23%)	67 (17%)	
V	22 (3.3%)	11 (4.1%)	11 (2.8%)	
Anthropometrics				
Body height (cm)	153 (12) [116, 191]	152 (11) [116, 176]	154 (13) [123, 191]	0.025
Body weight (kg)	47 (12) [18, 89]	46 (11) [18, 81]	47 (13) [25, 89]	0.5
BMI (kg/m^2)	19.7 (3.2) [13.1, 34.8]	19.9 (3.1) [13.1, 31.8]	19.6 (3.2) [14.0, 34.8]	0.19
20-m shuttle run test				
HR max (bpm)	204 (8) [175, 228]	205 (8) [179, 228]	203 (9) [175, 228]	0.057
HR mean (bpm)	184 (10) [135, 209]	185 (10) [135, 205]	184 (10) [137, 209]	0.16
rHR mean (% HR max)	90.3 (2.9) [73.4, 97.0]	90.31 (3.25) [73.4, 95.8]	90.37 (2.61) [74.8, 96.9]	0.77
Distance (m)	1312 (449) [320, 2700]	1116 (351) [360, 1960]	1436 (460) [320, 2700]	**< 0.001**
VO_2max (mL/kg/min)	46 (7) [30, 64]	43 (5) [30, 55]	48 (7) [30, 64]	**< 0.001**

Note: Continuous variables are presented as mean (standard deviation) [range], and categorical variables are reported as frequency (percentage).
Abbreviations: BMI, body mass index; HR, heart rate; PAQ-A, Physical Activity Questionnaire for Adolescents; PAQ-C, Physical Activity Questionnaire for Children; PHV, peak height velocity; rHR, relative heart rate.

reported higher physical activity levels (PAQ scores), were taller, and demonstrated longer shuttle run distances and higher estimated VO_2max ($p < 0.001$). No significant sex differences were observed in body weight ($p = 0.5$), BMI ($p = 0.19$), or %HRmax ($p = 0.77$). Most participants were in Tanner stages II-III.

3.2 | Hs-cTnT

Baseline and postexercise hs-cTnT concentrations are presented in Table 2. At baseline, 61% of participants had values below the LoD, and 2.5% exceeded the URL. Postexercise, 36% remained below the LoD, while 7.5% exceeded the URL. More than half of the sample responded to exercise with an increase in hs-cTnT (56%). Specifically, the odds of response were higher than those of nonresponse (OR = 1.65), and the relative risk of response was 1.28. Proportionally more girls exceeded the URL postexercise (12%) compared to boys (4.6%). The estimated 99th percentile postexercise was 31.42 ng/L (95% CI: 21.78–49.96), with sex-specific estimates of 33.19 ng/L for boys and 32.85 ng/L for girls. The median delta hs-cTnT (post–pre) was 1.5 ng/L (IQR: 0.0–3.5), with similar increases observed in girls (1.8 ng/L, IQR: 0.0–3.8) compared to boys (0.9 ng/L, IQR: 0.0–3.3) ($p = 0.27$).

3.3 | Effect of Exercise and Sex

Results from the linear mixed-effects model are presented in Table 3. Fixed effects were assessed using Type III ANOVA. There was a main effect of time ($F(1, 1426) = 239$, $p < 0.001$) and no main effect of sex ($F(1, 1426) = 0.04$, $p = 0.85$), although the time × sex interaction was statistically significant ($F(1, 1426) = 5.38$, $p = 0.021$). Estimated marginal means (back-transformed from the log scale) for hs-cTnT are shown by sex and time: girls—baseline 2.40 ng/L (95% CI 2.18–2.63) and 3 h postexercise 4.15 ng/L (95% CI 3.82–4.51); boys—baseline 2.61 ng/L (95% CI 2.42–2.82) and 3 h postexercise 3.92 ng/L (95% CI 3.65–4.19). Pairwise contrasts of time within sex (post–pre;

TABLE 2 | Baseline, postexercise, and exercise-induced change in hs-cTnT concentrations.

	Overall ($n = 733$)	Girls ($n = 296$)	Boys ($n = 437$)	*p*
Baseline				
hs-cTnT < LoD	439 (61%)	192 (67%)	247 (58%)	0.014
Serum hs-cTnT (ng/L)	1.50 (1.50, 4.04) [1.50, 40.50]	1.50 (1.50, 3.85) [1.50, 40.50]	1.50 (1.50, 4.11) [1.50, 32.80]	0.079
hs-cTnT > URL	18 (2.5%)	12 (4.1%)	6 (1.4%)	0.021
99th percentile	16.58 (14.5, 21.8)	15.85 (12.4, 40.5)	18.21 (13.5, 29.5)	
3 h postexercise				
hs-cTnT < LoD	255 (36%)	92 (32%)	163 (38%)	0.124
hs-cTnT (ng/L)	4.1 (1.5, 6.4) [1.5, 56.1]	4.2 (1.5, 6.5) [1.5, 53.4]	3.8 (1.5, 6.2) [1.5, 56.1]	0.306
hs-cTnT > URL	55 (7.5%)	35 (12%)	20 (4.6%)	**< 0.001**
99th percentile	31.42 (18.1, 24.0)	32.85 (21.4, 53.4)	33.19 (21.7, 54.8)	
Δ hs-cTnT (post–pre)				
Δ hs-cTnT (post–pre) (ng/L)	1.5 (0.0, 3.5) [−6.1, 51.9]	1.8 (0.0, 3.8) [−6.1, 51.9]	0.9 (0.0, 3.3) [−4.4, 50.8]	0.27
hs-cTnT increase from baseline (3 h)	399 (56%)	160 (57%)	239 (56%)	0.814
hs-cTnT no change form baseline	189 (27%)	70 (25%)	119 (28%)	0.38
hs-cTnT decrease from baseline (3 h)	122 (17%)	52 (18%)	70 (16%)	0.472

Note: hs-cTnT concentrations are reported as median (interquartile range) [range], and categorical variables are reported as frequency (percentage).
Abbreviations: hs-cTnT, high-sensitivity cardiac troponin T; LoD, limit of detection; URL, upper reference limit (99th percentile).

TABLE 3 | Linear mixed-effects model of log-transformed hs-cTnT.

Parameter	Coefficient	95% CI	*t* (df)	*p*
Fixed effects				
Intercept	1.22	(1.16, 1.29)	36 (1426)	**< 0.001**
Time [3 h]	0.42	(0.35, 0.49)	101.5 (1426)	**< 0.001**
Sex [male]	0.06	(−0.02, 0.15)	1.4 (1426)	0.16
Time [3 h] × sex [male]	−0.11	(−0.20, −0.02)	−2.32 (1426)	0.021
Random effects				
Participant	0.38	(0.35, 0.42)		
Residual	0.43	(0.41, 0.46)		
Model performance				
Sigma: 0.43	AIC: 8636.93	BIC: 8668.53	R^2 (conditional): 0.49	R^2 (marginal): 0.09

Note: Results from a linear mixed-effects model with log-transformed hs-cTnT concentration as the dependent variable. Fixed effects include time (baseline/3 h postexercise), sex, and their interaction. Participant ID was included as a random intercept. R^2 (marginal) represents the variance explained by fixed effects; R^2 (conditional) represents total variance explained including random effects.
Abbreviations: AIC, Akaike Information Criterion; BIC, Bayesian Information Criterion; CI, confidence interval.

contrasts on the log scale) were: girls, estimate change 0.42 ng/L (SE 0.036), $t(718) = 11.5$, $p < 0.001$; boys, estimate change 0.31 ng/L (SE 0.03), $t(711) = 10.4$, $p < 0.0001$. Model performance indices were: conditional $R^2 = 0.49$ and marginal $R^2 = 0.09$. Figure 1 shows the visualization of individual changes.

3.4 | Covariate Effects on Hs-cTnT Response

Covariate-specific models are summarized in Figure 2. Several participant characteristics were associated with higher baseline hs-cTnT concentrations, including older age, higher PHV

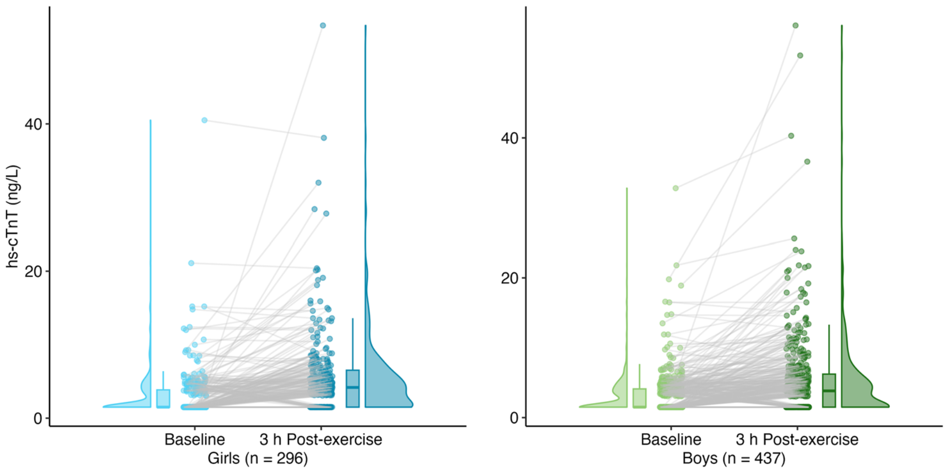

FIGURE 1 | Individual kinetics of hs-cTnT concentrations before and after exercise, stratified by sex. hs-cTnT concentrations at baseline and 3 h postexercise are shown for girls (left panel, $n=296$) and boys (right panel, $n=437$). Each panel includes half-violin plots indicating the distribution density, boxplots showing the median and interquartile range, individual data points representing participant values, and gray lines connecting paired values to illustrate within-subject changes. Colors indicate sex and time points.

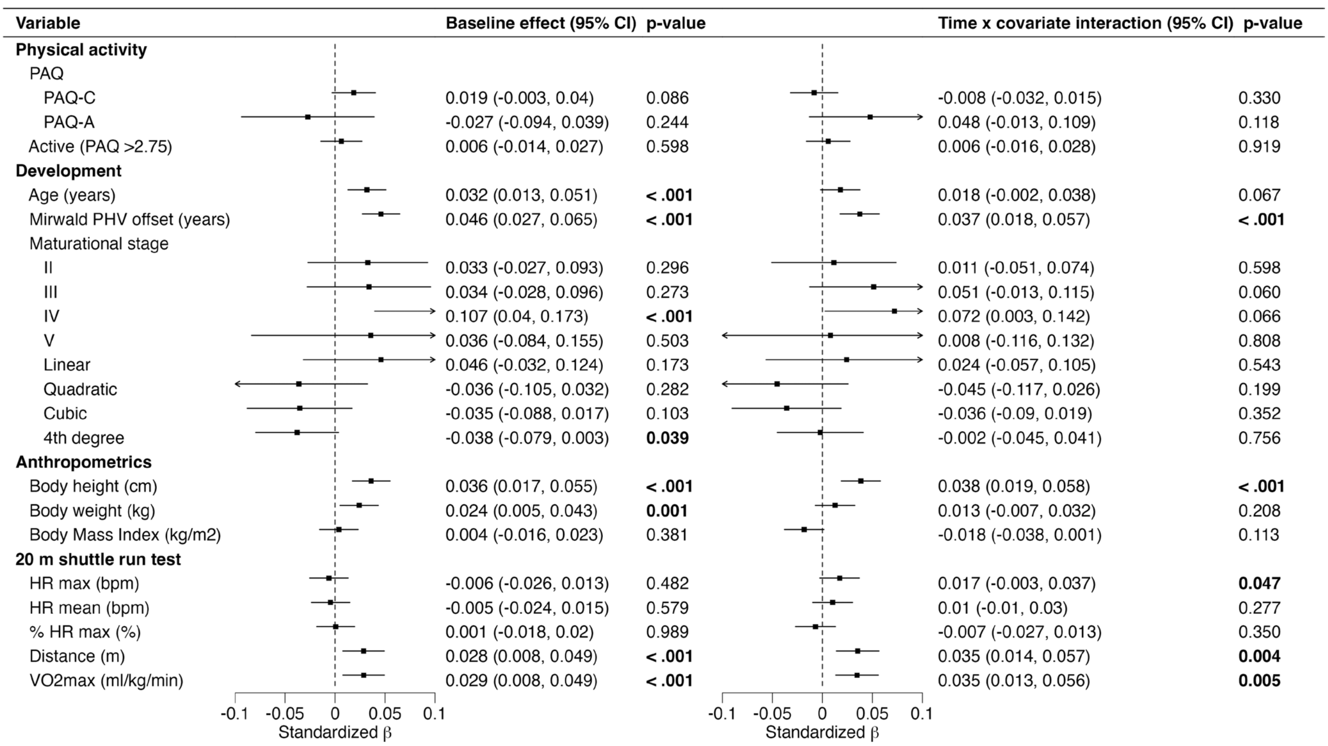

FIGURE 2 | Standardized baseline and interaction effects of individual covariates on log-transformed hs-cTnT levels. Points represent standardized β coefficients and horizontal lines represent 95% confidence intervals. Baseline effects (left panel) correspond to the association between each covariate and preexercise log1p(hs-cTnT). Exercise effects (right panel) correspond to the time × covariate interaction term, reflecting covariate-dependent differences in the pre- to 3 h postexercise change in log1p(hs-cTnT). Arrows indicate confidence intervals extending beyond the plotting range.

offset, maturational stage IV, greater body height and weight, longer 20mSRT distance, and higher VO_2max. Regarding the exercise-induced hs-cTnT response, significant interaction effects were observed for PHV offset, body height, HRmax, shuttle run distance, and VO_2max, indicating that individuals with more advanced biological maturity, greater stature, and superior cardiorespiratory fitness tended to exhibit greater elevations in hs-cTnT following exercise. Conversely, physical activity scores were not significantly related to hs-cTnT kinetics.

4 | Discussion

This study demonstrates that 20mSRT significantly increases hs-cTnT levels in a large pediatric cohort, with subtle differences in release patterns between sexes. However, these demographic and exercise-related factors explained only a small fraction of the variance compared to individual differences. Ultimately, the findings confirm that exercise-induced hs-cTnT release is a highly heterogeneous phenomenon driven primarily by unmeasured intrinsic factors.

A central finding of our analysis is that while exercise drives a common increase in hs-cTnT, individual responses vary dramatically. The low marginal R^2 (0.09) in our model indicates that standard variables such as time and sex account for very little of the hs-cTnT response. In contrast, the much higher conditional R^2 (0.49) highlights that participant-level effects are the strongest contributors, indicating that individual characteristics are the primary drivers of hs-cTnT release. This high degree of interindividual variability in hs-cTnT response is documented in the literature, where some individuals present marked elevations in hs-cTnT ("responders"), while others display minimal or no changes ("nonresponders") under nearly identical exercise conditions [6, 16].

Our results indicate a nuanced association between sex and hs-cTnT kinetics. Although no main effect of sex was observed, indicating comparable overall hs-cTnT concentrations between girls and boys. However, a small but statistically significant time × sex interaction was detected. This interaction reflects a slightly greater exercise-induced increase in hs-cTnT in girls, who had marginally lower baseline estimates but reached similar, or in some cases slightly higher, concentrations at 3 h postexercise compared with boys. The magnitude of this difference was modest and accounted for only a small proportion of the overall variability, which is consistent with previous studies reporting minimal or no sex-related differences in exercise-induced hs-cTnT release [9, 11, 23]. Given the limited effect size and the large interindividual variability observed, this finding should be interpreted cautiously and does not support a dominant role of sex in determining hs-cTnT responses to exercise in youth.

The study demonstrates an association between postexercise hs-cTnT levels and specific variables such as PHV offset, body height, run distance, and VO_2max. Specifically, we observed a positive association with Tanner stage 4 maturation and body height, consistent with previous research [8]. This association may be attributed to a more extensive training history and higher fitness level, enabling a greater capacity for effort during exercise. This, in turn, may result in higher HRmax [7]. Similarly, the positive association with VO_2max and run distance aligns with other findings [10, 31], suggesting that the link between cardiorespiratory fitness and myocardial response may stem from the ability to sustain greater exercise intensities. This challenges the hypothesis that "less trained" or "less developed" hearts tend to exhibit higher hs-cTnT levels after exercise [32]. Conversely, we found no statistically significant association between PAQ scores and postexercise hs-cTnT response. This aligns with previous work examining the effects of weekly training volume, which also found no consistent association with the magnitude of postexercise hs-cTnT elevation [9]. Notably, elevations in hs-cTnT were observed across the cohort regardless of reported activity levels. This further emphasizes the heterogeneity of the response and supports the conclusion that underlying determinants of exercise-induced hs-cTnT release remain largely unexplained by traditional exercise variables [3, 11].

4.1 | Strength and Limitations

To our knowledge, this is the first study to examine exercise-induced hs-cTnT release in such a large and heterogeneous pediatric cohort, with a substantial representation of girls. The large sample size and broad range of maturational stages, fitness levels, and physical activity profiles enhance the external validity of the findings and provide a comprehensive overview of hs-cTnT responses in youth. In addition, the use of the 20mSRT, a widely implemented and ecologically valid field-based assessment, enhances the practical relevance of the results.

Some limitations should be acknowledged. Participants were recruited from schools and organized sport settings, which may limit extrapolation to completely sedentary populations. Moreover, hs-cTnT was assessed only at baseline and 3 h postexercise, preventing a full characterization of individual hs-cTnT release kinetics. Finally, although the 20mSRT test reflects real-world exercise conditions, its incremental nature implies that exercise duration and workload are inherently not identical across participants.

5 | Conclusion

In conclusion, the 20mSRT induced a significant increase in hs-cTnT concentrations in children and adolescents. More than half of the participants showed a postexercise rise in hs-cTnT, with a marked interindividual variability in the magnitude of the response. Sex, maturational status, anthropometric characteristics, and cardiorespiratory fitness were associated with the hs-cTnT response, but together explained only a small proportion of the overall variability. These findings indicate that exercise-induced hs-cTnT release in youth is a common but highly heterogeneous phenomenon, largely influenced by individual-specific factors not fully captured by conventional demographic or exercise-related variables.

6 | Perspective

From a practical standpoint, isolated postexercise hs-cTnT elevations in youth should be interpreted with caution and within the clinical and exercise context. Future studies should focus on characterizing individual-specific patterns of hs-cTnT responsiveness to better understand the determinants of this heterogeneous response. Furthermore, identifying the biological mechanisms underlying this release is essential. Methodologically, implementing serial blood sampling would allow for a more precise characterization of release kinetics compared to single time-point assessments. In this context, the integration of advanced imaging approaches and novel hs-cTnT-related analytical strategies may help to further elucidate the pathways involved in exercise-induced cardiomyocyte stress across diverse pediatric populations.

Author Contributions

Conceptualization: Joaquin Reverter-Masia and Alejandro Legaz-Arrese. Methodology: Enric Conesa-Milian. Software: Abraham Batalla-Gavaldà. Validation: Vicenç Hernández-González, Alejandro Legaz-Arrese, and Isaac López-Laval. Formal analysis: Rafel Cirer-Sastre. Investigation: Francesc Corbi. Resources: Isaac López-Laval. Data curation: Rafel Cirer-Sastre and Abraham Batalla-Gavaldà. Writing – original draft preparation: Enric Conesa-Milian. Writing – review and editing: Alejandro Legaz-Arrese. Visualization: Enric Conesa-Milian and Joaquin Reverter-Masia. Supervision: Vicenç Hernández-González. Project administration: Joaquin Reverter-Masia. Funding acquisition: Joaquin Reverter-Masia. All authors have read and agreed to the published version of the manuscript.

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Consent

Informed consent was obtained from all participants and their legal guardians prior to any data collection as part of the protocol procedures.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data presented in this study are available on request from the corresponding author due to ethical restrictions related to the protection of sensitive information and privacy of underage participants, in accordance with institutional and data protection regulations.

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