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Article

Cross-sectional Associations among Fitness, Dyslipidemia, Body Adiposity Indexes and Type 2 Diabetes Mellitus Risk in Adolescents

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Abstract: The prevalence of type 2 diabetes mellitus (T2DM) in adolescents is rising, correlating with the global increase in obesity and physical inactivity. This study aims to examine the individual and combined associations of cardiorespiratory fitness (CRF), atherogenic index of plasma (AIP), conicity index (C-index), visceral adiposity index (VAI), and the product of triglyceride and glucose (TyG) with fasting plasma glucose (FPG), an established marker of type 2 diabetes mellitus (T2DM) in Nigerian adolescents. This cross-sectional study included a sample of 403 adolescents (201 girls and 202 boys) aged 11–19 years. Participants were assessed for all independent and dependent variables using standard procedures. Regression models adjusted for age and sexual maturity were used to determine the associations between these health markers and T2DM risk. Among the high-risk adolescents, 56.6% were at risk of central obesity, 49.1% had low fitness, 46.2% were susceptible to insulin resistance, and 33.5% had dyslipidemia. After controlling for confounding variables, all health markers were independently and jointly associated with T2DM risk, with TyG displaying the strongest explanatory power (females: $\beta = 2.163$, $p = 0.001$; males: $\beta = 0.748$, $p < 0.001$). Females with elevated TyG indices were 46.6 times more likely to be at risk of T2DM, while the odds of males having high TyG being at risk of T2DM was 3.6. Health markers were independently and jointly associated with T2DM risk in adolescents, with TyG, C-index, and VAI contributing most significantly. Promoting healthy diet, weight management and endurance physical activities among adolescents is crucial for improving metabolic health.

Keywords: adolescents; central adiposity; fitness; insulin resistance; metabolic health; type 2 diabetes

1. Introduction

Type 2 diabetes mellitus (T2DM) is a chronic metabolic disease associated with severe complications and comorbid conditions, including retinopathy, end-stage renal disease, metabolic syndrome (MetS), and cardiovascular disease (CVD) [1]. Its global prevalence is increasing at an alarming rate, primarily due to aging populations and the adoption of Western lifestyles. Currently, T2DM is ranked as the ninth leading cause of mortality worldwide [2]. Although traditionally considered a disease of middle-aged and older adults, the rising incidence of T2DM among children and adolescents is a growing public health concern [3]. This increase has been linked to the global surge in pediatric obesity and declining physical activity levels [4]. Consequently, early screening and identification of at-risk youth should be prioritized as a critical public health goal.

The primary pathophysiological characteristic of T2DM is insulin resistance (IR), which leads to hyperglycemia—the hallmark of the disease [5]. Insulin resistance is a

metabolic condition in which insulin-sensitive tissues, such as skeletal muscle, liver, and adipose tissue, exhibit diminished responsiveness to insulin [6]. Impaired fasting plasma glucose (FPG) is a well-established biomarker of T2DM and, along with IR and impaired glucose tolerance, is strongly associated with obesity—a recognized risk factor for the disease [7]. While obesity is a known predictor of several cardiometabolic diseases (CMDs) [8,9], research has shown that the distribution of adipose tissue, rather than total fat alone, is more closely associated with these conditions [10,11].

To better capture visceral fat dysfunction, Amato and colleagues [12] developed the Visceral Adiposity Index (VAI), a mathematical model that has been validated as a reliable predictor of CMD, including T2DM [13,14]. Similarly, the Conicity Index (C-index), which estimates central fat distribution [15], has also been identified as a strong predictor of MetS and diabetes [16,17]. Cardiorespiratory fitness (CRF), an objective measure of habitual physical activity, is another key indicator of overall health. Low CRF has been strongly linked with IR and T2DM risk [14]. Its role in both predicting and managing T2DM and other CMDs is well recognized [13,18]. Among the numerous risk factors for CVD, dyslipidemia remains a major concern. The triglyceride-to-high-density lipoprotein cholesterol (TG/HDL-C) ratio, often referred to as the Atherogenic Index of Plasma (AIP), is a robust biomarker for MetS —a known precursor to T2DM in both adults [19] and adolescents [20]. AIP has been positively associated with IR and cardiovascular events in adults [21], and has also been linked to IR, carotid intima-media thickness, and elevated fasting blood glucose in children and adolescents [22,23]. Furthermore, the Triglyceride-Glucose (TyG) index—a product of fasting triglyceride and glucose levels has shown high accuracy in identifying IR [24], and several studies among Caucasian populations have demonstrated a strong association between TyG and the onset of diabetes [25,26].

Nigeria, like many developing countries, is experiencing a rapid transition in lifestyle patterns, which has led to a surge in chronic health issues, even among adolescents. This developmental stage is often characterized by risky behaviors such as substance abuse, unhealthy dietary habits, sedentary behavior, and excessive screen time—all of which can contribute to the early onset of non-communicable diseases [27]. While existing studies have highlighted the negative impact of low physical fitness and traditional cardiometabolic risk factors on chronic disease risk in youth populations [20,28], there remains a paucity of data on the role of novel or non-traditional risk markers in predicting T2DM risk among adolescents, particularly in Africa. Additionally, the diagnostic utility of these novel markers in detecting early T2DM risk in adolescents has not been sufficiently explored.

This study, therefore, aimed to examine the associations between CRF, AIP, VAI, C-index, and TyG index with FPG among Nigerian adolescents. Specifically, it sought to determine the independent relationships between these health markers and FPG, identify the marker most strongly associated with FPG, and evaluate their predictive capacities for identifying T2DM risk in this population. Understanding the interrelationships among these variables is crucial for early identification of at-risk adolescents and for developing effective health promotion and disease prevention strategies. This study seeks to address a significant gap in pediatric research and

contribute to early intervention efforts aimed at mitigating T2DM risk during adolescence.

2. Materials and Methods

2.1. Study Design and Setting

This cross-sectional study involved male and female secondary school students aged 11 to 19 years, selected from schools in Kogi East, North Central Nigeria. Kogi State, with Lokoja as its capital, is situated in Nigeria's North-Central geopolitical zone. Data collection was conducted over a four-month period (September to December 2019). Limited data exist on adolescent lifestyles in this region, particularly regarding physical fitness and other lifestyle behaviors and their implications for health.

2.2. Study Population and Sampling

Adolescent participants were randomly selected from four secondary schools within the study area, using Slovin's formula to determine an appropriate sample size [29]. This yielded a minimum of 399 participants, which was increased to 418 to enhance representativeness and account for potential attrition and missing data. A systematic sampling technique was employed-every fourth student on the class list was selected, beginning from a predetermined starting point.

Inclusion criteria comprised students with no history of CVD or other known health conditions, and those who had not participated in an organized exercise program for at least six months prior to data collection. Details of the pilot testing have been previously reported [20].

The present study conformed with the principles embodied in the Helsinki Declaration and was approved by the Ethical Review Committee of the College of Health Sciences, Kogi State University, Nigeria (Ref. No. COHS/02/25/2020). Written informed consent of participants was provided by parents/guardians and participants gave their assent prior to data collection.

2.3. Data Collection Procedures

Two visits were made to each participating school. During the first visit, anthropometric, clinical, and biochemical data were collected. The second visit was dedicated to physical fitness testing. All tests were conducted in a standardized sequence by the same members of the research team to ensure consistency and reliability.

2.4. Physical Characteristics Measurements

Anthropometric assessments were carried out using standardized procedures [30], and included measurements of stature, body mass, body fat percentage, waist circumference (WC), and body mass index (BMI). Participants were assessed without footwear and wearing light clothing to ensure accurate anthropometric measurements. Body mass was measured to the nearest 0.1 kg using a calibrated digital scale (Seca Model Sec-880; Seca, Birmingham, UK), while stature was recorded to the nearest 0.1

cm with a wall-mounted stadiometer (Seca Model Sec-206; Seca, Birmingham, UK). From these values, body mass index (BMI) was calculated by dividing weight in kilograms by the square of height in meters (kg/m²), serving as a proxy measure for body fat. Using their BMIs, participants were categorized as having a healthy weight or being overweight using the revised FitnessGram standards [31]. Details of the procedures have been previously reported [20]. Central adiposity was assessed using the C-index, calculated with the equation developed by Valdez [15].

$$\text{C-index} = \frac{\text{waist circumference (m)}}{0.109\sqrt{\frac{\text{body weight (kg)}}{\text{height (m)}}}}$$

Sexual maturity was estimated using the predictive equation by Moore et al. [32], based on chronological age and stature. Maturity offset (MO), defined as the time before or after peak height velocity, was calculated, and age at peak height velocity (APHV)—age or period of fastest growth in height in adolescents, was derived as the difference between age and MO accordingly.

2.5. Fitness Testing

Cardiorespiratory fitness was assessed using the Progressive Aerobic Cardiovascular Endurance Run (PACER) test, which involves shuttle runs of increasing intensity. Participants were verbally encouraged to continue running until volitional fatigue. The PACER is a validated predictor of peak oxygen uptake ($\dot{V}O_{2\,peak}$ [$mL \cdot kg^{-1} \cdot min^{-1}$]) in youth [33]. Based on sex- and age-specific FitnessGram standards, participants were classified as having either high or low fitness [30]. Thresholds were set at 23–61 laps for females and 32–94 laps for males. Those meeting or exceeding these thresholds were considered to have high fitness; those falling below were classified as having low fitness.

2.6. Blood Pressure Measurements

Systolic and diastolic blood pressures were measured using a digital blood pressure monitor (HEM-705 CP; Omron, Tokyo, Japan) after a 10-minute seated rest. Measurements were taken on the non-dominant arm, and the average of three readings was used for analysis. Hypertension thresholds were defined based on established clinical standards [34].

2.7. Biochemical Measurements

Fasting blood samples were collected from capillary pricks between 9:00 and 11:00 a.m. to assess total cholesterol (TC), low-density lipoprotein cholesterol (LDL-C), high-density lipoprotein cholesterol HDL-C, TG, and FPG. The Cardio-Check Plus Analyzer (CCPA; PTS Diagnostics, Indianapolis, IN, USA) was used, following validated protocols [35]. Detailed description of the protocol has been reported [20].

The VAI was computed using Amato and Giordano's formula [36]:

$$\text{VAI(girls)} = \left(\frac{\text{WC}}{39.58} + [1.89 \times \text{BMI}]\right) \times \left(\frac{\text{TG}}{0.81}\right) \times \left(\frac{1.52}{\text{HDL} - \text{C}}\right)$$

$$\text{VAI(boys)} = \left(\frac{\text{WC}}{39.68} + [1.88 \times \text{BMI}]\right) \times \left(\frac{\text{TG}}{1.03}\right) \times \left(\frac{1.31}{\text{HDL} - \text{C}}\right)$$

The TyG, a surrogate marker of IR and T2DM, was calculated using the formula proposed by Simental-Mendia et al. [24].

$$\text{TyG} = \ln\left(\frac{\text{TG} \times \text{FPG}}{2}\right)$$

Where TG and FPG are converted to mg/dl for the calculation.

2.8. Definition of Cardiometabolic Disease Risks

Cardiometabolic disease risks were defined using criteria established by the International Diabetes Federation (IDF) [37]: FPG (≥ 5.6 mmol/L), HDL-C (≤ 1.04 mmol/L), and TG (≥ 1.7 mmol/L). The cut-off for the C-index was set at the 90th percentile for age and sex, following the method described by Filgueiras et al. [38].

To determine the cut-off values for the VAI and the TG/HDL-C ratio, both indicators of CMD risk, the sample was divided into tertiles. The minimum value of the highest tertile was used as the cut-off point. For the total sample, the minimum value in the highest tertile for VAI was 1.35 for girls and 1.1 for boys. For the TG/HDL-C ratio, the values were 1.0 for girls and 1.1 for boys. Given the lack of established reference values for VAI and TG/HDL-C ratio in pediatric populations, this approach is considered a valid and robust estimate of CMD risk. It has been employed in several previous studies [39,40].

2.9. Data Analysis

Following data coding and cleaning, statistical analyses were performed using IBM SPSS (Version 20; IBM Corporation, Armonk, NY, USA). Statistical significance was set at $p \leq 0.05$. Descriptive statistics included means, standard deviations, frequencies, and percentages. The Kolmogorov–Smirnov test was used to assess normality of the data distribution. Between-sex differences in study variables were evaluated using independent samples t-tests or, when appropriate, the Mann–Whitney U test. Relationships among health markers and their relative contributions were examined through multivariate regression models, adjusted for age and maturity status. In model 1, only the covariates – age and maturity status, were related to FPG. In model 2, health markers were added while controlling for these covariates. Logistic regression analysis was used to evaluate the independent associations between health markers and T2DM risk. Odds ratios (ORs) for being at risk were calculated across categories of independent variables, with adjustments made for age and maturity status. Receiver Operating Characteristic (ROC) curve analysis was employed to assess the predictive power of the independent variables in predicting FPG, using a 95% confidence interval (CI). Area under the curve (AUC), sensitivity (Se), and specificity (Sp) values were reported to identify optimal thresholds for T2DM risk. AUC values were interpreted according to Hosmer and Lemeshow's criteria [41].

3. Results

Out of 418 adolescents who met the eligibility criteria, data from 403 participants were included in the final analysis. Data from 15 individuals were

excluded due to absenteeism and incomplete responses, yielding a compliance rate of 96%. Participants' anthropometric, clinical, and biochemical characteristics by sex are summarized in Table 1. Males demonstrated significantly more favorable values in most health markers ($p < 0.05$) than females. No significant sex differences were observed for the remaining variables. Sixty-two adolescents, 30 females and 32 males were at risk of T2DM. This translated to an average prevalence of 15.3% (Females = 7.4%; Males = 7.9%). The sex-specific prevalence rates are apparently similar.

Table 1. Physical and cardiometabolic disease risk characteristics of participants (n = 403).

Variable	Total (n = 403)	Girls (n = 201)	Boys (n = 202)	t-value	p-value
Age (y)	14.7 ± 2.3	14.8 ± 2.3	14.7 ± 2.2	0.586	0.558
APHV (y)	13.3 ± 1.1	12.5 ± 0.8	14.1 ± 0.8	20.068	< 0.001
MO (y)	1.4 ± 1.3	2.3 ± 1.7	0.6 ± 1.0	10.029	< 0.001
Height (cm)	160.2 ± 9.8	159.6 ± 7.1	160.9 ± 11.9	0.303	0.193
Weight (kg)	53.1 ± 12.5	55.5 ±12.1	50.8 ± 12.5	3.784	0.016
BMI ($Kg \cdot m^{-2}$)	20.5 ± 3.5	21.7 ± 4.0	19.3 ± 2.6	6.929	< 0.001
WC (cm)	65.8 ± 8.8	67.2 ± 9.4	64.4 ± 8.0	2.273	0.001
CRF (lap)	32.2 ± 16.8	24.9 ± 13.3	39.5 ± 16.8	9.697	< 0.001
TG ($mmol \cdot L^{-1}$)	1.0 ± 0.9	1.1 ± 1.2	0.9 ± 0.4	1.653	0.100
HDL-C ($mmol \cdot L^{-1}$)	1.3 ± 0.4	1.3 ± 0.3	1.3 ± 0.4	1.090	0.276
TG/HDL-C	0.9 ± 0.6	1.0 ± 0.6	0.8 ± 0.5	1.697	0.091
C-index	1.1 ± 0.1	1.1 ± 0.1	1.1 ± 0.1	0.672	0.502
VAI	1.2 ± 0.7	1.6 ± 0.8	0.8 ± 0.6	3.912	< 0.001
TyG	8.0 ± 3.9	8.2 ± 5.1	7.7 ± 1.9	1.255	0.211
FPG ($mmol \cdot L^{-1}$)	5.1 ± 0.7	5.0 ± 0.7	5.1 ± 0.7	0.401	0.157

BMI: Body mass index; WC: Waist circumference; CRF: Cardiorespiratory fitness; TG: Triglyceride; HDL-C: High-density lipoprotein cholesterol; TG/HDL-C: Triglyceride-to-high density lipoprotein cholesterol; C-index: Conicity index; VAI: Visceral adiposity index; TyG: Triglyceride-glucose index; FPG: fasting plasma glucose.

Table 2 presents the comparison of T2DM risk status, stratified into "no risk" and "at risk" subgroups. Except for the endurance run where girls were at increased risk, boys generally exhibited a more unfavorable risk profile. Figure 1 presents the proportion of participants at risk of T2DM stratified by sex. A higher proportion of females were at risk of VAI, while males were more vulnerable to other risk factors. Overall, the most prevalent risk factors were elevated VAI (56.6%), low CRF (49.1%), and high TyG (46.2%), with boys appearing more susceptible across these domains (Figure 1). Sex-specific prevalence rates for each health marker are as follows: CRF (female = 47.8%; Male = 50.5%); C-index (Female = 13.9%; Male = 13.9%); AIP (Female = 33.3%; Male = 33.7%); VAI (Female = 65.2%; Male = 48.0%); TyG (Female = 37.3%; Male = 55.0%).

Table 2. Comparison of health markers according to T2DM risk status (n = 403).

Variable	Girls			Boys		
	No risk (n = 165)	**Risk (n = 36)**	**Total (n = 201)**	**No risk (n = 194)**	**Risk (n = 08)**	**Total (n = 202)**
Age (year)	14.6 ± 2.3	15.9 ± 2.0	14.8 ± 2.3	14.5 ± 2.1	15.3 ± 2.4	14.7 ± 2.2[b]
WC	66.6 ± 8.9	75.1 ± 11.9	67.2 ± 9.4	64.1 ± 7.8	70.8 ± 10.6	64.4 ± 8.0
CRF	25.7 ± 13.9	21.1 ± 9.3	24.9 ± 13.3[a]	42.2 ± 15.4	31.1 ± 18.4	39.5 ± 16.8[a]
C-index	1.1 ± 0.1	1.1 ± 0.1	1.1 ± 0.1	1.0 ± 0.1	1.2 ± 0.1	1.1 ± 0.1
TyG	8.3 ± 5.5	8.0 ± 1.3	8.2 ± 5.1	7.3 ± 1.5	9.1 ± 2.1	7.7 ± 1.9[a]
TG/HDL-C	1.0 ± 1.0	0.8 ± 0.7	0.9 ± 1.7	0.7 ± 0.4	1.0 ± 0.6	0.8 ± 0.5[b]
VAI	1.7 ± 3.0	1.4 ± 1.1	1.6 ± 2.8	0.7 ± 0.4	1.2 ± 0.7	0.8 ± 0.6[a]

[a]: $p < 0.001$; [b]: $p < 0.05$. WC: Waist circumference; CRF: Cardiorespiratory fitness; C-index: Conicity index; TyG: Triglyceride-glucose index; TG/HDL-C: Triglycerides-to-High-density lipoprotein cholesterol; VAI: Visceral adiposity index

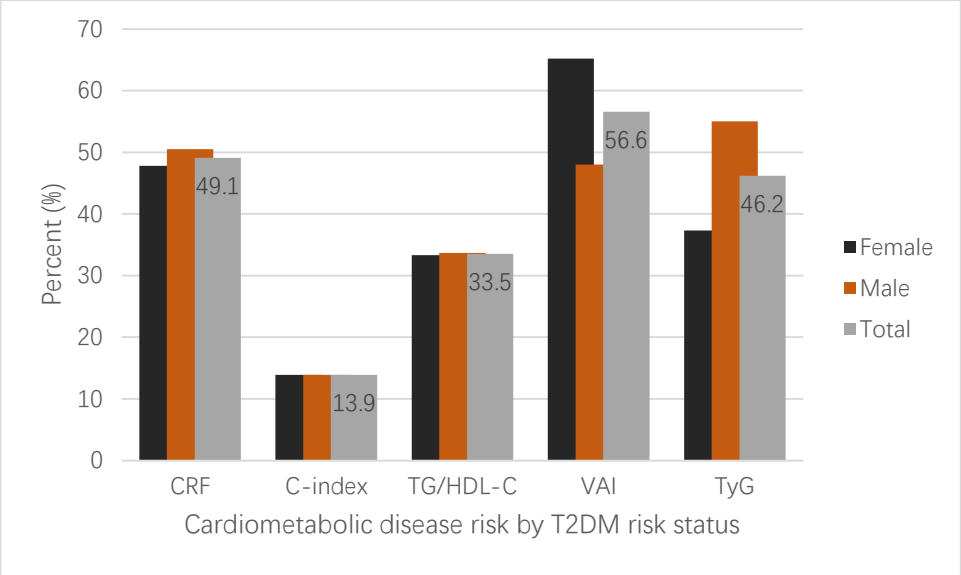

Figure 1. Cardiometabolic disease risk factors of participants at risk of T2DM by sex. CRF: Cardiorespiratory fitness; C-index: Conicity index; TG/HDL-C: Triglyceride-to-high density lipoprotein cholesterol; VAI: Visceral adiposity index; TyG: Triglyceride-glucose index.

Multivariate regression analyses assessing the predictive power of independent variables on T2DM risk are presented in Table 3. In both sexes, the dependent variable was significantly associated with TyG, VAI, and C-index ($p < 0.05$), with TyG ($p < 0.001$) and VAI ($p < 0.001$) demonstrating the strongest impact. Among females, the covariates in Step 1 accounted for 6.7% of the variance in T2DM risk. Adding the health markers in Step 2 increased the total explained variance to 20.2%, indicating that the independent variables contributed an additional 13.5% ($p < 0.001$) after adjusting for covariates. For males, the model explained 46.4% of the variance ($p < 0.001$), with 29.9% attributed to the independent variables. Further analysis revealed that, in females, each unit increase in TyG was associated with a 1.5 mmol increase in FPG. In males, a unit increase in TyG corresponded to a 0.5 mmol increase. Regarding VAI, each unit increase was associated with a mean rise of 1.2 mmol in girls and 0.9 mmol in boys. Details of the results are presented in Table 3.

Table 3. Standardized regression coefficients assessing the relationships among health markers and T2DM.

Sex	Predictor	Model 1		Model 2	
		β	**p value**	**β**	**p value**
Females	Age	−0.236	0.385	−0.339	0.228
	MO	0.480	0.077	0.519	0.056
	CRF	-	-	−0.012	0.875
	C-index	-	-	0.039	0.656
	TG/HDL-C	-	-	0.427	< 0.480
	VAI	-	-	1.678	0.005
	TyG	-	-	2.163	0.001
Males	Age	1.360	< 0.001	0.219	< 0.377
	MO	−1.230	< 0.001	0.069	0.783
	CRF	-	-	0.022	0.759
	C-index	-	-	0.461	0.002
	TG/HDL-C	-	-	0.687	0.281
	VAI	-	-	1.270	0.057
	TyG	-	-	0.748	< 0.001

MO: Maturity off-set; CRF: Cardiorespiratory fitness; C-index: Conicity index; TG/HDL-C: Triglyceride-to-high density lipoprotein cholesterol; VAI: Visceral adiposity index; TyG: Triglyceride-glucose index; β: Standardized regression coefficients.

Binary logistic regression models (adjusted for age and maturity status) showed that in females, TyG (OR = 46.6; $p < 0.001$) and CRF (OR = 3.38; $p = 0.021$) were significantly associated with T2DM risk. In males, TyG (OR = 3.64; $p < 0.001$) and age (OR = 3.1; $p = 0.003$) emerged as significant predictors. Detailed results are provided in Table 4.

Table 4. The odds of risk of T2DM among participants ($n = 403$).

Group	Predictor		Odds Ratio	95% CI	p value
Female	CRF	Low	1		
		High	3.38	1.21–9.49	0.021
	C-index	High	1		
		Low	0.12	0.02–0.67	0.015
	VAI	High	1		
		Low	0.19	0.04–0.98	0.048
	TyG	High	1		
		Low	46.6	7.45–284.77	< 0.001
Male	Age		3.1	1.46–6.49	0.003
	TyG	High	1		
		Low	3.64	1.08–12.26	0.001

CRF: Cardiorespiratory fitness; C-index: Conicity index; VAI: Visceral adiposity index; TyG: Triglyceride-glucose index

Table 5 and Figure 2 display the results of ROC curve analyses. Among females, only TyG showed a significant AUC (69.9%, $p < 0.001$). In males, all variables except CRF ($p = 0.059$) demonstrated significant AUC values ($p < 0.05$). As diagnostic tools

for T2DM risk, C-index (80.8%) in males presented the strongest predictive capability. Across all models, sensitivity was high while specificity was low, suggesting that these markers effectively identified most adolescents at risk for T2DM, albeit with a tendency to overlook some at-risk individuals. Details of the results are shown in Table 5.

Table 5. Receiver operating characteristics curve analysis for T2DM risk among participants.

Group	IV	AUC	95%CI	Cut-point	Se	Sp	p value
Females	CRF	0.397	0.307-0.487	21.5	0.389	0.558	0.053
	C-index	0.518	0.414-0.622	1.13	0.500	0.327	0.733
	AIP	0.542	0.448–0.637	0.67	0.556	0.406	0.425
	VAI	0.548	0.446–0.650	1.26	0.556	0.327	0.369
	TyG	0.699	0.625–0.773	7.55	0.722	0.297	< 0.001
Males	CRF	0.347	0.291–0.470	34.5	0.347	0.614	0.059
	C-index	0.808	0.738–0.878	1.13	0.796	0.261	< 0.001
	AIP	0.615	0.509–0.721	0.59	0.633	0.569	0.015
	VAI	0.674	0.576–0.772	0.70	0.694	0.412	< 0.001
	TyG	0.784	0.714–0.853	6.98	0.776	0.431	< 0.001

IV: Independent variable; CRF: Cardiorespiratory fitness; C-index: Conicity index; AIP: Atherogenic index of the plasma; VAI: Visceral adiposity index; TyG: Triglyceride-glucose index

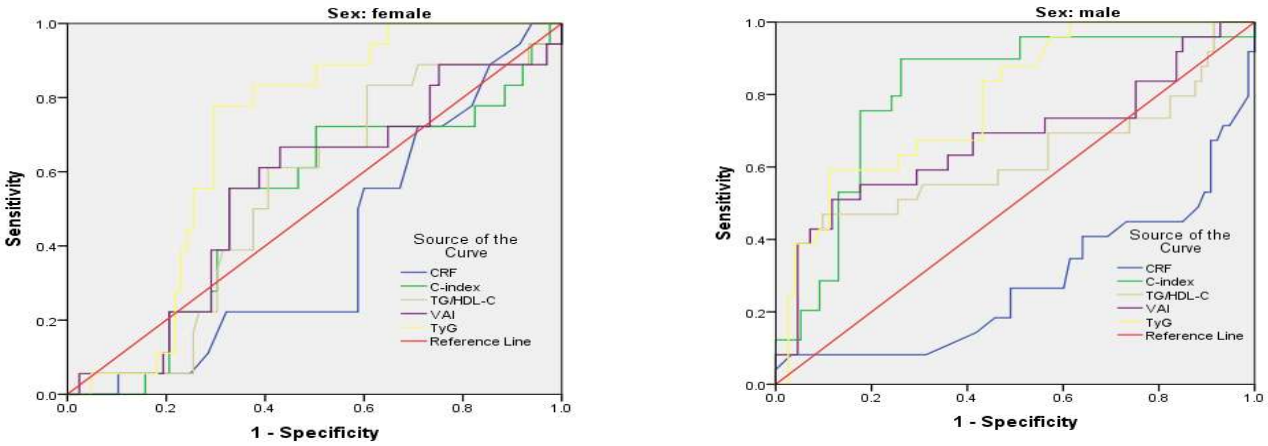

Figure 2. Sex-specific areas under the curves of health markers for T2DM risk. CRF: Cardiorespiratory fitness; C-index: Conicity index; TG/HDL-C: Triglyceride-to-high-density lipoprotein cholesterol; VAI: Visceral adiposity index; TyG: Triglyceride-glucose index

4. Discussion

This cross-sectional study examined the associations between cardiorespiratory fitness (CRF), conicity index (C-index), atherogenic index of plasma (AIP), visceral adiposity index (VAI), and glucose-triglyceride index (TyG) with fasting plasma glucose (FPG)—a key marker of type 2 diabetes mellitus (T2DM) among Nigerian adolescents. The main findings indicate a moderate prevalence of T2DM risk, with similar rates observed across sexes. Participants with elevated FPG levels exhibited significantly higher mean scores for most health risk factors. Overall, a considerable proportion of adolescents were at risk for VAI, TyG, and low CRF, with males demonstrating a higher prevalence of these risks. Notably, only a few of the health markers showed significant individual and combined associations with T2DM risk, with TyG displaying the strongest explanatory power. All markers, except CRF, demonstrated predictive capacity for T2DM risk among males, while only TyG was effective in identifying at-risk females.

4.1. Cardiometabolic Characteristics of Participants

The study revealed a prevalence of impaired FPG at 15.3%, with comparable rates between sexes. This figure aligns closely with the 14.5% reported among Ivorian adolescents [42] but is lower than the 18.4% prevalence observed in American adolescents [43]. Conversely, the 3.3% reported for Chinese adolescent boys is significantly lower than the rate observed in this study. Additionally, the prevalence documented here exceeds the pooled global (8.84%) and African (12.32%) estimates for prediabetes in youth [44]. These findings suggest a concerning trend of elevated blood glucose abnormalities among Nigerian adolescents, warranting urgent public health attention and interventions aimed at reversing this trajectory.

Adolescents at higher risk for T2DM in this study exhibited significantly elevated mean values for most cardiometabolic indicators. This finding is consistent with previous research [7,45], which links T2DM risk in youth to dyslipidemia, visceral adipose tissue dysfunction, and other metabolic risk factors. In our sample, a higher proportion of adolescents, especially males were at risk for elevated VAI, low CRF, and high TyG compared to other markers. The molecular cytopathological effects of these health indicators on T2DM involve a complex interplay of metabolic, inflammatory, and cellular dysfunctions. For instance, CRF exerts protective effects by enhancing mitochondrial function and insulin sensitivity while reducing proinflammatory cytokines—factors that collectively promote better glucose regulation [28]. In contrast, elevated levels of the VAI and the TyG contribute to the development of T2DM by increasing lipotoxicity, oxidative stress, inflammation, IR, and beta-cell dysfunction—all of which facilitate the onset of T2DM [45–47]. These results highlight the importance of implementing targeted interventions-including health education, improved nutrition, and increased physical activity, to mitigate future T2DM risk.

4.2. Associations Between Health Markers and T2DM Risk

The results indicate that the examined health markers are independently and collectively associated with T2DM risk, with TyG showing the greatest explanatory

value regardless of sex (Table 3). This aligns with previous studies [19,46], where TyG, a surrogate marker of IR was strongly linked to T2DM. TyG is also closely correlated with visceral adiposity, which carries higher metabolic risks than subcutaneous fat. Like VAI, TyG reflects visceral fat accumulation, which is often accompanied by elevated levels of pro-inflammatory biomarkers such as C-reactive protein (CRP), interleukin-6 (IL-6), and tumor necrosis factor-alpha (TNF-α). These biomarkers are indicative of the low-grade systemic inflammation commonly observed in obesity-related metabolic disorders, including metabolic syndrome and T2DM [47,48].

The prominent role of TyG in this study suggests that interventions aimed at reducing visceral fat may be effective in lowering T2DM risk among adolescents. C-index, a proxy for central obesity, was strongly associated with T2DM risk among females. C-index specifically reflects VAT, which secretes inflammatory cytokines and adipokines that promote IR, central to T2DM pathogenesis [16,45]. Several studies have demonstrated a significant association between high C-index and insulin resistance, even in individuals with normal BMI [7,19]. Given its cost-effectiveness and simplicity, C-index could serve as a valuable screening tool for early detection and prevention of T2DM risk. In this study, AIP was not significantly associated with the risk of T2DM in participants, regardless of sex. This lack of association may be attributed to the generally low AIP values observed in the study population (see Tables 1 and 2).

4.3. Diagnostic Utility of C-index, TyG, and VAI

Among the biomarkers evaluated, C-index and TyG demonstrated the highest diagnostic capacities for detecting T2DM risk in males, while only TyG showed diagnostic utility among females. The AUC of 80.8% for C-index indicates good predictive accuracy, particularly in males. However, TyG yielded only fair AUC values, consistent with findings in both Chinese adolescents [46] and adults [48]. The higher TyG AUC in males compared to females suggests a stronger diagnostic performance in male adolescents within this population. In general, the C-index and TyG index are more effective at identifying males at risk of diabetes.

The practicality of the TyG index, given its affordability, accessibility, and noninvasive nature, makes it a promising tool for early identification and intervention. Integrating TyG and C-index assessments into school- or community-based health surveillance programs could facilitate early lifestyle modifications, potentially preventing the onset of T2DM in adulthood.

4.4. Implications for Practice

The substantial variance in T2DM risk explained by health markers in this study has significant public health implications. Specifically, the variance accounted for was 13.5% in females and 29.9% in males, indicating that the model explained a remarkable proportion of the variance in T2DM risk among adolescents. These findings indicate that these health markers have strong associations with T2DM risk, especially in males. These findings highlight the urgent need for effective school- and community-based health promotion efforts aimed at improving metabolic health. Key

focus areas should include promoting a healthy diet, weight management, and maintaining an active lifestyle to mitigate future health risks.

This study offers critical insights into sex-specific determinants of T2DM risk in adolescents. Among female adolescents, the odds of a participant with elevated TyG being at risk of T2DM are 46.6 times higher than those of their peers with favorable index. This stark disparity underscores the detrimental role of TyG, likely due to its strong association with pro-inflammatory biomarkers and insulin resistance. These unusually high odds in the female participants are a cause for concern. Additionally, females with poor CRF were 3.4 times more likely to be at risk of T2DM compared to the peers with favorable fitness levels, emphasizing the protective effect of cardiorespiratory fitness on metabolic health in girls. In contrast, male adolescents with high TyG levels were 3.6 times more likely to be at risk of T2DM compared to those with lower indices, suggesting that insulin resistance may play a relatively less critical role in the metabolic health of males. The observed sex-specific disparities, with females exhibiting greater vulnerability to disease risk, indicate that central adiposity may play a pivotal role in the metabolic health of adolescent girls. This association is likely influenced by sex-specific fat distribution patterns, hormonal regulation, and behavioral factors during pubertal development. These differences call for sex-specific preventive strategies. For female adolescents, targeted interventions that improve insulin sensitivity and metabolic health may offer significant benefits. In males, a broader focus on overall metabolic health beyond insulin levels may be more effective in reducing T2DM risk.

The findings further support the need for early, multifactorial interventions addressing modifiable risk factors such as visceral adiposity and low CRF. Public health strategies should prioritize routine screening using cost-effective and feasible indicators like TyG and the C-index, especially among high-risk adolescent populations. Integrating these indices into regular school health assessments could improve early detection and facilitate evidence-based preventive strategies.

4.5. Limitations and Strengths

A key limitation of this study is its cross-sectional design, which cannot determine causality between health markers (CRF, AIP, VAI, C-index and TyG) and T2DM risk. Another limitation is the exclusive inclusion of in-school adolescents, excluding out-of-school youths, who may have different risk profiles. This will limit the generalizability of findings across the broader adolescent population in Nigeria. Additionally, this study controlled for age and sexual maturity only; no control for other potential confounders like sedentary time, physical activity, diet, socioeconomic status, family history and sleep patterns-all of which influence metabolic health in adolescents. Furthermore, indirect estimations of BMI and VAI were used, which may be less accurate than direct or laboratory-based measures such as dual-energy X-ray absorptiometry, magnetic resonance imaging, or computed tomography.

Despite these limitations, a major strength of the study is the use of ROC analysis, which allowed for the identification of population-specific thresholds for various health markers. This approach enabled a nuanced assessment of T2DM risk, as adolescents with elevated TyG, VAI, and C-index were found to be at increased risk

of T2DM regardless of sex. Moreover, the use of TyG as a proxy for insulin resistance is both cost-effective and practical compared to the Homeostatic Model Assessment of Insulin Resistance (HOMA-IR), which, though considered the gold standard, is less feasible in low-resource settings.

5. Conclusions

This study highlights the susceptibility of Nigerian adolescents to T2DM risk and identifies key metabolic markers-TyG, C-index, and VAI as independent predictors. While TyG and C-index were particularly associated with increased risk in males, the combined influence of all independent variables on T2DM risk was moderate. Health promotion programs should prioritize balanced nutrition, effective weight control strategies, and regular endurance-based physical activity to help maintain optimal glucose levels and improve long-term metabolic health in adolescents, especially among males. Future longitudinal research is essential to better understand the predictive roles of CRF, C-index, AIP, TyG, and VAI in assessing T2DM risk in youth populations.

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Data Availability Statement: Data supporting the findings of this study are available from the corresponding author, DIM, upon reasonable request.

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