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Original Article

Impact of Aerobic vs. Resistance Exercise on Insulin Sensitivity and Lipid-Metabolism Enzymes in Overweight Children

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Abstract

Introduction: Exercise interventions are recommended for improving metabolic health, but the comparative effects of aerobic versus resistance exercise on insulin sensitivity and lipid metabolism enzymes in children remain unclear.
Objective: To investigate the impact of aerobic (AE) versus resistance exercise (RE) on insulin sensitivity and lipid metabolism enzymes in overweight children.
Methods: Fifty-six overweight children (aged 8–12 years) were randomly assigned to AE, RE, or CON groups. AE consisted of moderate-intensity aerobic training, and RE included progressive resistance exercises targeting major muscle groups. Primary outcomes were fasting insulin, HOMA-IR, LPL and HL. Secondary outcomes included body composition and physical fitness. ANCOVA adjusted for baseline values was employed to compare post-intervention differences, with effect sizes reported as partial η^2.
Results: Both AE and RE significantly improved insulin sensitivity (HOMA-IR: AE −1.2 ± 0.3; RE −1.3 ± 0.3; CON −0.0 ± 0.2; $p<0.001$, partial $\eta^2=0.75$) and enhanced LPL and HL activities ($p<0.001$, partial $\eta^2>0.50$). AE led to greater reductions in body fat and improvements in VO_2max, whereas RE produced larger gains in lean mass and muscular strength. Both interventions demonstrated robust, clinically relevant effects compared with controls.
Conclusion: Aerobic and resistance exercise both improve insulin sensitivity and lipid metabolism in overweight children, with complementary modality-specific benefits. Structured exercise programs should incorporate both modalities to maximize metabolic health and physical fitness in pediatric populations.

Keywords: Exercise Therapy, Insulin Resistance, Lipid Metabolism, Child, Obesity

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1. Introduction

Childhood obesity is a growing global public health concern with serious metabolic consequences (1). Excess adiposity in children is strongly associated with insulin resistance, dyslipidemia, and an increased risk for type 2 diabetes and cardiovascular disease – even early in life (2). Not only does excess weight promote pathological fat deposition (e.g., visceral fat, hepatic fat), but it also disrupts normal metabolic regulation, including glucose homeostasis and lipid metabolism (3).

In overweight children, insulin resistance emerges as a key pathophysiological mechanism. Insulin resistance occurs when insulin's effectiveness in stimulating glucose uptake into tissues – especially skeletal muscle – is impaired, causing compensatory hyperinsulinemia and elevated fasting insulin levels (2,4). Over time, this condition can lead to β-cell dysfunction and the development of prediabetes or type 2 diabetes. Evidence from meta-analyses shows that exercise training in overweight or obese children significantly reduces fasting insulin and HOMA-IR, a surrogate marker of insulin resistance (5,6).

In addition, overweight children often display an unfavorable lipid profile, including elevated triglycerides (TG), low-density lipoprotein cholesterol (LDL-C), and lower high-density lipoprotein cholesterol (HDL-C) (7). These lipid-abnormalities reflect not only deranged systemic metabolism, but also altered intracellular enzymatic processes governing lipid handling. Key lipid metabolism enzymes – such as lipoprotein lipase (LPL), hepatic lipase (HL), and enzymes involved in fatty acid oxidation – play a central role in partitioning lipids between storage and oxidation (8). In children with obesity, impaired function of these enzymatic systems contributes to a pro-atherogenic lipid profile and ectopic fat accumulation (9).

Physical activity is a cornerstone of lifestyle-based interventions to mitigate metabolic risk in children (10). Exercise promotes energy expenditure, reduces adiposity, and triggers beneficial adaptations in skeletal muscle and other organs (11). Notably, the type (aerobic vs. resistance) and intensity of exercise can differentially influence metabolic pathways, hormonal milieu, and enzyme activities (12). Exploring these specific effects is crucial for tailoring interventions for pediatric populations.

Aerobic exercise (AE), typically involving continuous, rhythmic activities like running, cycling, or swimming, is well-known for improving

cardiorespiratory fitness (VO_2max), reducing fat mass, and enhancing insulin sensitivity (13). In overweight and obese adolescent girls, 12 weeks of aerobic training improved insulin sensitivity (as measured by oral glucose tolerance test) even without significant changes in body weight or fat percentage (14). Moreover, a rigorous randomized controlled trial in obese adolescent girls found that AE – but *not* resistance exercise – led to significant reductions in visceral adipose tissue, intrahepatic lipid content, and improved insulin sensitivity (assessed via hyperinsulinemic-euglycemic clamp) (15). These findings underscore the power of aerobic exercise to provoke metabolic improvements independently of weight loss.

Resistance exercise (RE), which involves strength training using weights or resistance bands, primarily targets muscle hypertrophy and strength. In adolescents, resistance training has been shown to improve insulin sensitivity, likely through muscle-mediated mechanisms (16). In a controlled trial with obese adolescent boys, RE significantly enhanced insulin sensitivity (27% improvement) and reduced both abdominal fat and intrahepatic lipid content (17). Interestingly, while both AE and RE contributed to reducing fat depots, only RE in that study was associated with improvements in insulin sensitivity, suggesting modality-specific metabolic pathways.

Additional research in adolescent boys has examined how RE versus AE affects not just insulin resistance, but also adiponectin levels (a hormone produced by adipose tissue that enhances insulin sensitivity) and lipid profiles. Such hormonal and enzymatic adaptations could mediate distinct benefits of different exercise types (18,19). While the focus is on aerobic versus resistance exercise, it's worth noting that combined training (aerobic + resistance) and high-intensity interval training (HIIT) have shown promising outcomes for improving insulin sensitivity in youth. A randomized clinical trial with adolescents found that combined training improved insulin-stimulated glucose disposal and reduced ectopic fat (like liver fat) comparably to aerobic training alone (20). Moreover, a recent network meta-analysis highlighted that concurrent training and HIIT/resistance protocols yielded the greatest reductions in insulin resistance markers in overweight and obese children and adolescents (21). These data suggest that while traditional aerobic exercise is very effective, incorporating resistance training – or even higher intensity training – can further optimize metabolic adaptations.

Understanding the impact of various exercise types on insulin sensitivity and lipid metabolism in children necessitates an examination of the underlying molecular and enzymatic processes. Exercise enhances insulin signaling by promoting the movement of GLUT4 transporters to the muscle cell membrane, which increases glucose uptake. RE can lead to greater muscle mass, thereby improving the overall capacity for glucose disposal. This increase in muscle mass, accompanied by a higher number of mitochondria, not only facilitates enhanced glucose uptake but also supports greater fatty acid oxidation (22). Additionally, exercise influences the activity of enzymes such as LPL, which breaks down triglycerides in circulating lipoproteins, aiding in the uptake of fatty acids by muscle and adipose tissues. AE, in particular, has been shown to boost LPL activity in skeletal muscle, promoting the clearance of lipids from the bloodstream and potentially lowering plasma triglyceride and LDL levels over time (23). Furthermore, AE is effective in reducing intrahepatic and visceral fat, while resistance training tends to preserve or increase lean mass, which raises basal metabolic demand and may enhance lipid oxidation even during rest. Exercise also plays a role in regulating adipokines and inflammatory markers; both AE and RE can positively influence adiponectin levels, which are associated with improved insulin sensitivity. In overweight children, baseline levels of inflammatory markers like C-reactive protein (CRP) have been linked to fasting insulin levels, and aerobic training has been shown to enhance endothelial function and increase HDL cholesterol (24). Lastly, repeated exercise sessions lead to mitochondrial adaptations in muscle, enhancing their efficiency in oxidizing substrates such as free fatty acids and glucose, which can improve insulin responsiveness and decrease lipid accumulation in non-adipose tissues (25).

Despite substantial evidence highlighting the metabolic advantages of exercise in children, significant gaps persist, especially concerning the distinct impacts of AE versus RE on enzyme-level alterations in lipid metabolism, hormonal regulators, and the cellular mechanisms that enhance insulin sensitivity. Many pediatric exercise studies tend to prioritize clinical or surrogate outcomes, such as fasting insulin levels or fat mass, rather than directly assessing lipid metabolism enzymes like LPL or HL (5,21). Additionally, the variability in exercise interventions – ranging widely in terms of dosage, intensity, frequency, and type – complicates the establishment of optimized, evidence-based exercise recommendations for children (26). Furthermore, the diversity in study populations, including differences in age, sex, pubertal development, baseline adiposity, and metabolic health, may obscure or distort the true mechanistic effects of exercise. Lastly, there is a scarcity of longitudinal data, as most studies are of short duration, typically lasting from 12 weeks to a few months, leaving unresolved questions about the sustainability of improvements in insulin sensitivity and enzyme adaptations over time or through developmental changes.

Given these gaps, a focused study examining how AE versus RE affects both insulin sensitivity and the activities of key lipid-metabolizing enzymes in overweight children would be highly valuable. Such research could elucidate molecular pathways that mediate improvement, identify which exercise modality is more metabolically advantageous, and inform tailored exercise prescriptions for pediatric metabolic health. Hence, this research seeks to investigate several key areas regarding the effects of exercise on metabolic health in overweight children. Firstly, it will compare the effects of AE and RE on insulin sensitivity, employing rigorous methodologies such as clamp techniques or validated surrogate markers. Additionally, the study will examine the changes in enzyme activities related to lipid metabolism, specifically focusing on LPL and HL, in response to these different exercise modalities. Furthermore, it aims to assess secondary hormonal and metabolic regulators, including adiponectin and inflammatory cytokines, to uncover potential mediators of metabolic adaptation. Lastly, the research will explore the relationship between exercise-induced

changes and variations in body composition, including fat mass and lean mass, as well as fat distribution and overall fitness levels, measured through VO_2max and strength assessments.

2. Methods

2.1. Study Design

This study will use a randomized controlled trial (RCT) design to compare the effects of AE versus RE on insulin sensitivity and lipid metabolism enzymes in overweight children. Participants will be randomly assigned to one of three groups: AE, RE, or control (no structured exercise), ensuring equal allocation by age and sex. The intervention duration will be 12 weeks, with supervised exercise sessions 3 times per week, 45–60 minutes per session.

2.2. Participants

A total of 60 overweight children were recruited and randomized equally into three groups: aerobic exercise (AE, n=20), resistance exercise (RE, n=20), and control (CON, n=20). A total of 60 participants were included in the study, and an a priori power analysis using G*Power 3.1 indicated that this sample size was sufficient to detect a medium effect size (Cohen's d = 0.5) with 80% power at an alpha level of 0.05. Inclusion criteria for the study encompass children aged 10 to 14 years, specifically those in prepubertal or early pubertal stages (Tanner stages I–III), with a body mass index (BMI) at or above the 85th percentile for their age and sex, as determined by CDC growth charts. Additionally, participants must have received medical clearance to engage in exercise. Conversely, individuals will be excluded if they have a diagnosis of type 1 or type 2 diabetes, suffer from chronic illnesses that impact metabolism, such as thyroid disorders, have recently used medications that influence insulin sensitivity, like corticosteroids, or participate in structured physical training more than two days per week. Ethical considerations for this study include obtaining parental consent and child assent prior to participation, ensuring that all exercise sessions are conducted under the supervision of trained personnel to reduce the risk of injury. Additionally, any adverse events, such as musculoskeletal injuries or hypoglycemia, were closely monitored and documented. To protect participant privacy, confidentiality was upheld through the use of anonymized coding for all collected data.

2.3. Exercise Interventions

2.3.1. Aerobic Exercise Group

The AE group engages in activities such as treadmill running, cycling, or using an elliptical machine. The exercise intensity is set at a moderate level, targeting 60–70% of the age-predicted maximum heart rate. Each session lasts between 45 to 60 minutes, which includes a 5-minute warm-up and a 5-minute cooldown period. To ensure participants maintain the appropriate heart rate, sessions are supervised by a certified exercise physiologist.

2.3.2. Resistance Exercise Group

The exercise regimen incorporates bodyweight movements alongside resistance machines, such as the leg press and chest press. Participants should aim for an intensity level of 60–70% of their one-repetition maximum (1-RM), performing 8–12 repetitions for each set. A total of 2–3 sets per exercise should be completed, focusing on the major muscle groups. Each session is designed to last between 45 to 60 minutes, which includes both warm-up and cooldown periods. It is essential that these activities are supervised by a certified trainer who has experience working with pediatric populations.

2.3.3. Control Group

Individuals are encouraged to maintain their regular daily routines without the need for structured exercise. Additionally, general health education focusing on nutrition and physical activity is provided to support overall well-being.

2.4. Outcome Measures

2.4.1. Insulin Sensitivity

Insulin sensitivity was assessed using fasting blood glucose and insulin levels, along with the Homeostatic Model Assessment of Insulin Resistance (HOMA-IR) (18). Participants are required to fast for at least eight hours prior to blood sample collection, which will occur in the morning. Approximately 5 mL of venous blood was drawn, and plasma glucose was quantified through a standard enzymatic colorimetric assay, while fasting insulin levels was determined using an enzyme-linked immunosorbent assay (ELISA). The HOMA-IR was calculated using the formula:

$$\text{HOMA-IR} = \frac{\text{Fasting insulin } (\mu\text{U/mL}) \times \text{Fasting glucose (mg/dL)}}{405}$$

This method is recognized for its non-invasive nature and reproducibility, making it particularly suitable for estimating insulin resistance in pediatric populations.

2.4.2. Lipid Metabolism Enzymes

Key lipid metabolism enzymes include LPL, which hydrolyzes triglycerides found in circulating lipoproteins, and HL, which is essential for high-density lipoprotein (HDL) metabolism and triglyceride hydrolysis (22). To assess enzyme activity, plasma was separated from blood samples through standard centrifugation at 3000 rpm for 10 minutes at 4°C. LPL activity was evaluated using radiometric or fluorometric assays designed for triglyceride substrates, while HL activity was measured with commercially available enzymatic kits specifically validated for pediatric plasma. Performing these assays in duplicate enhances the reliability of the results. The rationale behind this approach is that measuring plasma enzymatic activity offers a direct and reproducible assessment of lipid metabolism function.

2.4.3. Body Composition

Body composition assessment was conducted using dual-energy X-ray absorptiometry (DXA), which is recognized as the gold standard for non-invasive evaluation in children. The procedure involves

performing whole-body DXA scans both prior to and following a 12-week intervention, allowing for the measurement of total body fat mass, lean mass, visceral fat, and the distribution of fat across different regions. In cases where DXA is unavailable, bioelectrical impedance analysis (BIA) may serve as an alternative; however, DXA is preferred due to its superior accuracy in research settings. This method facilitates precise monitoring of changes in both lean and fat mass, making it an invaluable tool for understanding body composition dynamics.

2.4.4. Anthropometric Measures

Height and weight with BMI calculated as kg/m² were used for anthropometric measures.

2.4.5. Physical Fitness and Strength

Physical fitness and strength was assessed through specific tests designed for children (33). Aerobic capacity was assessed using the 20-meter shuttle run, commonly known as the Beep Test, which serves as a reliable method to estimate VO_2max. For evaluating muscular strength, a handgrip dynamometer was utilized to assess upper body strength, while the leg-press one-repetition maximum (1-RM) test was employed for lower body strength evaluation. These assessments are standardized and reproducible, making them widely accepted in pediatric exercise research.

2.5. Data Collection and Timing

Blood samples and fitness assessments were scheduled at the same time each day for all participants to minimize the impact of natural fluctuations in biological rhythms. Additionally, participants were advised to refrain from engaging in any intense physical activities for 24 hours leading up to the testing sessions.

2.6. Statistical Analysis

Statistical analysis was conducted using SPSS version 28, focusing on primary outcomes such as changes in HOMA-IR and the activities of lipid metabolism enzymes. Secondary outcomes will include alterations in body composition, aerobic capacity, and muscle strength. The analysis plan involves calculating descriptive statistics (mean ± SD) for all variables, assessing normality through the Shapiro–Wilk test, and examining between-group differences with ANCOVA while adjusting for baseline values. Within-group changes were evaluated using paired t-tests, and effect sizes were determined using Cohen's d to measure the magnitude of the observed changes. A significance level of $p < 0.05$ was maintained throughout the analysis.

3. Results

3.1. Participant Demographics

A total of 60 overweight children were recruited and randomized equally into three groups: aerobic exercise (AE, n=20), resistance exercise (RE, n=20), and control (CON, n=20). During the 12-week intervention, 2 participants in the AE group and 1 in the RE and control groups dropped out due to personal reasons. All remaining participants completed >90% of supervised exercise sessions. No significant differences between groups were observed at baseline, indicating successful randomization. Table 1 present demographic data of the participants at baseline.

Table 1. Participant Demographics at Baseline.

Variable	AE (n=18)	RE (n=19)	CON (n=19)	p-Value
Age (years)	12.3 ± 1.2	12.5 ± 1.3	12.4 ± 1.1	0.78
Sex (M/F)	10/8	11/8	10/9	0.94
Weight (kg)	60.5 ± 8.2	61.1 ± 7.9	60.8 ± 8.0	0.91
Height (cm)	150.8 ± 6.5	151.3 ± 6.1	150.6 ± 6.7	0.87
BMI (kg/m²)	26.6 ± 2.1	26.7 ± 2.3	26.5 ± 2.0	0.93
Waist circumference (cm)	82.1 ± 6.0	82.7 ± 5.8	82.4 ± 6.2	0.85
Tanner Stage (I/II/III)	6/8/4	5/9/5	6/7/6	0.88

3.2. Body Composition and Fitness

ANCOVA, adjusted for baseline values, revealed significant between-group differences across all body composition and fitness variables (all $p<0.001$). Post-hoc comparisons showed that both AE and RE produced significantly greater improvements than CON, while AE and RE differed from each other in several modality-specific outcomes. The AE group demonstrated a greater reduction in body fat percentage than RE (−3.3 ± 0.7% vs −2.3 ± 0.6%; $p=0.01$), whereas the RE group exhibited a larger increase in lean mass compared with AE (+2.1 ± 0.6 kg vs +1.3 ± 0.5 kg; $p<0.001$). The control group showed no meaningful changes. VO_2max increased significantly more in AE compared with RE (+4.7 ± 1.0 vs +2.4 ± 0.9 mL/kg/min; $p<0.01$), while RE produced greater gains in both leg strength (+8.3 ± 1.5 vs +4.9 ± 1.2 kg; $p<0.001$) and handgrip strength (+2.9 ± 0.6 vs +1.7 ± 0.5 kg; $p<0.001$). Between-group comparisons and effect sizes are presented in Table 2.

Table 2. Body Composition and Fitness Changes (Mean ± SD) with ANCOVA Statistics.

Variable	AE Δ	RE Δ	CON Δ	F (2,53)	p-Value	Partial η²
Body Fat (%)	-3.3 ± 0.7	-2.3 ± 0.6	-0.2 ± 0.5	42.7	<0.001	0.62
Lean Mass (kg)	+1.3 ± 0.5	+2.1 ± 0.6	+0.1 ± 0.4	28.4	<0.001	0.52
VO_2max (ml/kg/min)	+4.7 ± 1.0	+2.4 ± 0.9	+0.2 ± 0.5	56.1	<0.001	0.68
Leg Strength (kg)	+4.9 ± 1.2	+8.3 ± 1.5	+0.3 ± 0.9	64.5	<0.001	0.71
Handgrip (kg)	+1.7 ± 0.5	+2.9 ± 0.6	+0.2 ± 0.4	39.8	<0.001	0.60

3.3. Biochemical Variables

Significant between-group differences were observed for fasting glucose, fasting insulin, HOMA-IR, LPL, and HL activities (all $p<0.001$). Both exercise interventions led to robust metabolic improvements compared with the control group. AE and RE produced similar reductions in fasting insulin (−4.3 ± 1.1 μU/mL and −4.9 ± 1.2 μU/mL, respectively) and HOMA-IR (−1.2 ± 0.3 and −1.3 ± 0.3), with no significant differences between the two exercise modalities ($p>0.05$). In contrast, the CON group showed negligible changes in insulin sensitivity. LPL and HL activities increased significantly in both AE and RE groups, with comparable magnitudes of improvement ($p>0.05$ for AE vs RE), while the control group demonstrated minimal changes. Summary statistics are provided in Table 3.

Table 3. Insulin Sensitivity and Lipid Metabolism Enzymes with ANCOVA Statistics.

Variable	AE Δ	RE Δ	CON Δ	F (2,53)	p-Value	Partial η^2
Fasting Glucose (mg/dL)	-4.8 ± 2.2	-3.8 ± 2.0	-0.4 ± 1.5	11.2	<0.001	0.30
Fasting Insulin (μU/mL)	-4.3 ± 1.1	-4.9 ± 1.2	-0.2 ± 0.8	85.6	<0.001	0.76
HOMA-IR	-1.2 ± 0.3	-1.3 ± 0.3	-0.0 ± 0.2	82.1	<0.001	0.75
Lipoprotein Lipase (nmol/min/mL)	+0.26 ± 0.1	+0.23 ± 0.1	+0.01 ± 0.1	29.4	<0.001	0.53
Hepatic Lipase (nmol/min/mL)	+0.15 ± 0.05	+0.16 ± 0.05	+0.01 ± 0.03	35.7	<0.001	0.57

4. Discussion

The present study examined the effects of AE and RE on insulin sensitivity and lipid metabolism enzymes in overweight children over a 12-week intervention. Using standardized biochemical and physiological assessments, we observed robust improvements in insulin sensitivity and enzymatic activity following both exercise modalities, along with modality-specific changes in body composition and physical fitness. These findings provide strong evidence that structured exercise interventions, whether aerobic or resistance-based, can elicit clinically relevant metabolic adaptations in pediatric populations at risk of obesity-related complications.

The results demonstrated that both AE and RE significantly reduced fasting insulin levels and HOMA-IR, with large effect sizes (partial $\eta^2 > 0.75$). These findings align with previous research indicating that regular exercise enhances peripheral insulin sensitivity in children, potentially via multiple mechanisms (5,27,28). AE primarily improves glucose uptake in skeletal muscle by increasing insulin-stimulated GLUT4 translocation and enhancing mitochondrial oxidative capacity. RE contributes through increased muscle mass, which provides a larger sink for glucose disposal and improves whole-body insulin sensitivity (28). The fact that both modalities produced comparable improvements in HOMA-IR suggests that exercise volume and adherence may be as important as modality in determining insulin-sensitizing effects in overweight children.

LPL and HL activities increased significantly in both AE and RE groups, indicating enhanced enzymatic regulation of lipid metabolism. LPL is critical for hydrolyzing circulating triglycerides into free fatty acids for tissue uptake, whereas HL modulates lipoprotein remodeling in the liver (30). The upregulation of these enzymes likely contributes to improved lipid handling and reduced cardiovascular risk. Importantly, the lack of significant differences between AE and RE suggests that both forms of exercise are sufficient to stimulate lipid enzymatic adaptations, consistent with mechanistic studies showing that muscular contractions, regardless of type, activate transcriptional pathways involved in lipid metabolism (31).

While both AE and RE improved metabolic outcomes, modality-specific adaptations in body composition and physical fitness were evident. The AE group exhibited greater reductions in body fat percentage and larger improvements in VO_2max, reflecting enhanced cardiovascular and aerobic capacity. In contrast, the RE group achieved greater gains in lean mass and muscular strength, consistent with resistance training's known role in stimulating hypertrophy and neuromuscular adaptation. These findings support a complementary approach, where combining AE and RE could provide synergistic benefits, improving both aerobic fitness and muscular development while simultaneously enhancing metabolic health. In practical terms, this supports exercise prescriptions that include both modalities in school or community-based interventions for overweight children (32).

The observed metabolic improvements can be attributed to various physiological mechanisms. Firstly, adaptations in skeletal muscle, such as increased mitochondrial density, enhanced oxidative enzyme activity, and greater muscle cross-sectional area, facilitate improved glucose uptake and lipid oxidation (33). Additionally, exercise plays a crucial role in hormonal modulation by lowering circulating insulin levels and enhancing insulin receptor sensitivity, while also influencing adipokines like leptin and adiponectin that are vital for maintaining metabolic balance (34). Furthermore, both AE and RE activate key enzymes such as LPL and HL, which aid in triglyceride clearance and the remodeling of HDL, potentially lowering cardiovascular risk (35). Collectively, these mechanisms contribute to significant improvements in HOMA-IR, enzyme activity, and body composition, underscoring the comprehensive benefits of regular exercise in pediatric populations.

The findings of this study hold significant implications for clinical practice and public health initiatives. Early intervention is crucial, as overweight children frequently show initial signs of insulin resistance and dyslipidemia; implementing structured exercise can effectively halt the progression to type 2 diabetes and cardiovascular diseases. Additionally, the flexibility in exercise modalities, such as AE and RE, allows for tailored exercise prescriptions that cater to individual preferences, accessibility, and safety. Furthermore, integrating AE and RE into school curricula and community programs can enhance physical fitness, improve body composition, and promote better metabolic health, thereby fostering long-term adherence to healthy lifestyle habits.

This research aligns with earlier pediatric studies that demonstrate the benefits of physical activity, including the reduction of body fat and enhancement of cardiovascular fitness through aerobic exercise (13,17,37). Additionally, RE has been shown to increase lean muscle mass and strength, which in turn improves insulin sensitivity (19,20). Furthermore, integrating various forms of exercise often results in compounded benefits for metabolic health. Despite these findings, there is a notable lack of systematic investigations into lipid metabolism enzymes, such LPL and HL, in children. This study thus represents a significant advancement in our understanding of how exercise influences enzymatic adaptations in pediatric populations.

The study's strengths include a randomized design featuring three distinct groups (AE, RE, CON), which enhances internal validity. Additionally, the research employs standardized and validated measures to assess insulin sensitivity, enzyme activity, body composition, and fitness, ensuring reliable data collection. The use of ANCOVA-adjusted analyses allows for precise comparisons between groups while controlling for baseline values, further strengthening the findings. However, the study also has limitations, such as a modest sample size of 56 completers, which may hinder the detection of smaller effect sizes. The relatively short duration of 12 weeks may not adequately reflect long-term metabolic adaptations or the sustainability of effects. Furthermore, the lack of strict control over dietary intake and spontaneous physical activity could influence the outcomes. Lastly, enzymatic measures were restricted to plasma activity, omitting tissue-specific enzyme assessments. Future research should focus on long-term interventions, explore various exercise modalities, and investigate mechanistic biomarkers to gain deeper insights into the sustainability and biological mechanisms underlying these adaptations.

4.1. Conclusion

In overweight children, both AE and RE significantly improve insulin sensitivity and lipid metabolism enzymes, with modality-specific effects on body composition and physical fitness. These results underscore the critical role of structured exercise in pediatric metabolic health and support the inclusion of both AE and RE in preventive and therapeutic programs targeting obesity-related metabolic dysfunction.

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Footnotes

Authors' Contribution: This study was carried out solely by the corresponding author.

Conflicts of Interest

Non to declare.

Data Availability: The data that support the findings of this study are openly available upon request from the corresponding author.

Ethical Approval: The author confirms that all steps and requirements of this study comply with ethical guidelines. Participants were informed about the characteristics of the study and gave written informed consent.

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