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Comprehending metabolic syndrome in children and adolescents: cardiometabolic outcomes in response to exercise

Comprendiendo el síndrome metabólico en niños y adolescentes: Efectos cardiometabólicos en respuesta al ejercicio

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Abstract. In recent years, the pandemic of obesity and metabolic syndrome (MetS) has gone from being a predominant problem in the adult population to becoming firmly established among children and adolescents. Precise data on the incidence and prevalence of MetS in children and adolescents are unreliable since the diagnosis is not guided by a standard definition adjusted to the characteristics of this population. A sedentary lifestyle has increased dramatically in the young population during the last years, where the influence of technology, high-calorie diets, and the lack of space, time, and interest in physical activity are the leading causes. Although various strategies must be implemented to counteract the increase in MetS cases in the young population, this review demonstrates the importance of physical exercise at a biochemical and physiological level as a critical prevention and treatment method, also presenting perspectives on how future research should be focused to acknowledge and cover this topic thoroughly.
Keywords: Children, adolescents, exercise, health, metabolic syndrome, obesity.

Resumen. En los últimos años, la pandemia de obesidad y síndrome metabólico (SMet) ha pasado de ser un problema predominante en la población adulta a consolidarse entre niños y adolescentes. Los datos precisos sobre la incidencia y prevalencia del SMet en niños y adolescentes no son fiables ya que el diagnóstico no se guía por una definición estándar ajustada a las características de esta población. El sedentarismo ha aumentado drásticamente en la población joven durante los últimos años, donde la influencia de la tecnología, las dietas hipercalóricas y la falta de espacio, tiempo e interés por la actividad física son las principales causas. Aunque se deben implementar diversas estrategias para contrarrestar el aumento de casos de SMet en la población joven, esta revisión demuestra la importancia del ejercicio físico a nivel bioquímico y fisiológico como método clave de prevención y tratamiento, presentando también perspectivas sobre cómo se deben enfocar las investigaciones futuras. para reconocer y cubrir completamente este tema.
Palabras clave: niños, adolescentes, ejercicio, salud, síndrome metabólico, obesidad.

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Introduction

Obesity is a serious public health issue that has been increasing among the young population aged 12 to 19 over the last decades, constituting a serious concern, considering that obesity is a risk factor for the appearance of prediabetic states such as metabolic syndrome (MetS). Besides poor eating habits, the rise in MetS incidence seems to be related to the sedentary lifestyle among the young population, with 81% of adolescents not complying with the minimum criteria to be considered physically active, according to the WHO (World Health Organization, 2024).

Therefore, it is highly relevant to understand the establishment of MetS pathophysiological alterations in the young population and their evolution as physical activity is involved as a therapeutic approach, considering that the molecular mechanisms associated with MetS and the adaptations induced by exercise have been described mainly in studies focused on the adult and elderly population.

Methods

An extensive search in electronic databases such as PubMed, Google Scholar, and Web of Science using combinations of at least two relevant search keywords (Metabolic syndrome, children, adolescents, exercise, health, obesity, sedentarism). Search terms were designed broadly to ensure the inclusion of as many relevant studies as possible, including studies in both English and Spanish.

Initially, the titles and abstracts of the retrieved studies were analyzed to determine their relevance to the topic. Some studies were excluded due to inadequate characteristics, such as those unrelated to the subject, were not human studies, presented unpublished data, or did not present empirical results. Potentially relevant studies were selected for full review. Given the non-systematic nature of this review, no formal assessment of the quality of the included studies was performed. However, the validity and relevance of the results were considered in the analysis of the findings.

A data extraction sheet was designed to collect relevant information, such as study design, sample, measures, and main findings. Then, a descriptive analysis of the extracted data was carried out, identifying patterns and areas of consensus or discrepancy between the studies. Narrative syntheses were conducted to provide an overview of the existing literature on the topic.

Metabolic syndrome

According to the WHO, about 650 million adults are currently living with obesity. Unfortunately, The World Obesity Federation anticipates this number will increase to 1 billion in the next decade (World Obesity Federation, 2022). This constitutes a serious concern, considering that obesity is a risk factor for other metabolic and cardiovascular diseases, such as type II diabetes mellitus (T2D), high blood pressure, dyslipidemia, and coronary heart disease, among others (Ezquerra et al., 2008; Han & Lean, 2016; Manna & Jain, 2015). Obesity-related physiological disturbances such as chronic systemic inflammation and immune system hyperactivation are the foundation for the emergence of Mets features (Esser et al., 2014). Broadly, MetS is defined as a cluster of metabolic disorders, including dyslipidemia, high blood pressure, and central obesity (Alberti et al., 2006). The NCEP-ATP III (National Cholesterol Education Program – Adult Treatment Panel III) definition of MetS has been the most accepted for a long time. The criteria indicate high fasting blood glucose (above 100 mg/dL or under treatment), high serum triglyceride (above 150 mg/dL or under treatment), low HDL cholesterol (below 40 mg/dL for males and 50 mg/dL for females, or under treatment), central obesity (waist circumference over 90 cm for males and 80 cm for females) and increased blood pressure (over 130/85 mmHg or under treatment); commonly the patient should present at least three of these signs for MetS diagnosis; nevertheless, the most up-to-date definition indicates that obesity must be one of those three signs (Dobrowolski et al., 2022; National Cholesterol Education Program, 2002).

Risk factors for MetS in children and adolescents

Several studies have demonstrated that genetic factors constitute a relevant risk factor for obesity and MetS emergence in children and adolescents; in fact, a child with obese parents is twice as likely to suffer from obesity (Whitaker et al., 1997). A meta-analysis studied genes involved in lipid and cholesterol metabolism, insulin signaling, and proinflammatory cytokines such as GNB3, PPARG, TCF7L2, APOA5, APOC3, APOE, CETP, FTO, and IL6 (Povel et al., 2011). Likewise, children of Black or Hispanic descent have a higher incidence of insulin resistance (IR) compared to Caucasians (Arslanian et al., 1996; Batey et al., 1997).

Interestingly, fetal programming explains the emergence of chronic non-communicable diseases in adulthood. For instance, gestational diabetes mellitus and malnutrition during pregnancy favor the development of MetS. Other factors that could alter epigenetics are a high-fat diet, inflammatory pathways, aging, and food availability, which can modify methylations in various genes involved with MetS parameters (Fathi Dizaji, 2018; Magge et al., 2017).

Lifestyle and gut microbiota also contribute to suffering MetS from childhood to adulthood. Dietary habits encompassing red processed meats, high-fat food, and low consumption of fiber are linked to greater cardiovascular risk, increased inflammation, and IR, while a diet rich in fruits and vegetables, fiber, and micronutrients increases insulin sensitivity and improves pancreatic function (Magge et al., 2017; Steinberger et al., 2009). Also, MetS impairs the Firmicutes and Bacteroidetes ratio in both adults and children, promoting obesity-associated inflammation (Codazzi et al., 2024).

Besides diet-based caloric intake, a determinant factor for MetS emergence is physical activity-induced caloric expenditure. ENSANUT 2018 determined an increase in the sedentary lifestyle among the young Mexican population, with 84.6% of children and adolescents not complying with the minimum criteria to be considered physically active (Instituto Nacional de Salud Pública (INSP), 2018). In this regard, the COVID-19 pandemic worsened the sedentary situation due to the decreased availability of spaces for physical activity and the lack of knowledge of effective exercise routines (Jiménez-Pavón et al., 2020). In addition, the pandemic mandatory confinement forced home-office and homeschooling, increasing the hours spent in front of screens; actually, children who watch less than 1 hour a day have less risk of being obese than those who watch 4 hours or more of television a day (Crespo et al., 2001).

Pathophysiology of MetS in children and adolescents

It is well established that MetS pathophysiology is multifactorial; however, the central MetS core is based on IR and obesity. IR is defined as a decrease in the tissue's response to insulin with its consequent reduction in glucose uptake and metabolic effects (Weiss et al., 2013). This state is caused mainly by the high level of free fatty acids (FFA) typical in obesity by the visceral adiposity accumulation (Lopez et al., 2023). Also, microbiota alteration induces the release of FFA, activating macrophages, contributing to the release of adipocytic hormones like adiponectin, apelin, and leptin, as well as proinflammatory cytokines such as IL-6, Tumor necrosis factor-alpha (TNF-α) and chemerin, which, along with the obesity-related reactive oxygen species production, leads to a systemic pro-inflammatory state (Kopp et al., 2003; Wassmann et al., 2004).

Moreover, the increased levels of FFA provoke alterations in glucose and lipid metabolism, stimulating lipogenesis and gluconeogenesis while decreasing glucose uptake by disrupting insulin signaling, hence inducing IR (Codazzi et al., 2024; Magge et al., 2017). These mechanisms increase triglyceride release, contributing to endothelial dysfunction and dyslipidemia (Bremer et al., 2012; Fadzlina et al., 2014; Weiss et al., 2013). Therefore, several researchers agreed that obesity constitutes the primary determinant of MetS development.

Concerning the release of adipokines in the MetS, the main one involved is leptin, which is elevated at a level directly proportional to the body fat percentage. At physiological conditions, leptin decreases food intake and stimulates energy expenditure; however, during obesity and overweight, high levels of leptin cause inflammation, thus promoting IR, atherosclerotic disease, and endothelial dysfunction (Codazzi et al., 2023).

On the other hand, adiponectin counteracts the pro-inflammatory effects of leptin, improving insulin sensitivity and endothelial function; as expected, this adipokine is decreased in MetS. Figure 1 summarizes the risk factors and metabolic disturbances associated with MetS development.

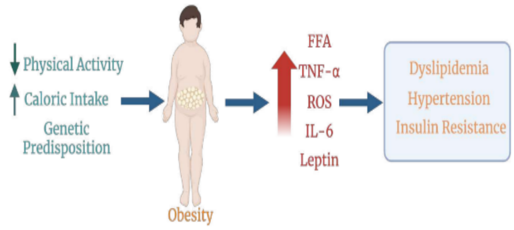

Figure 1. Risk factors and MetS pathophysiology evolution in children and adolescents. FFA: Free fatty acids; IL-6: Interleukin 6; ROS: reactive oxygen species; TNF-α: Tumor necrosis factor-alpha. Created with BioRender.com.

MetS diagnosis in children and adolescents

Due to the MetS-derived health complications, it is crucial to recognize its clinical signals at the earliest stage possible to reverse them. Although the criteria for adults are established, in the case of children and adolescents, the diagnosis is complex as the cut-point for the parameters needs to be determined. Thus, considering that it is a population in continuous growth and development with differences in fat distribution, insulin sensitivity, and hormonal profile, diagnostic parameters for adults should not be transcribed for children and adolescents (D'Adamo et al., 2011; Ortega-Cortes et al., 2016).

In this sense, MetS incidence in children and adolescents is not easily recognized since most definitions are based mainly on serum level parameters, which is an examination rarely solicited by pediatricians in apparently healthy children and adolescents, as well as body parameters, specifically waist circumference, that handle ranges that are not adapted to gender, ethnicity, and age (Weiss et al., 2003). As an initial attempt to assess MetS prevalence, in 2003, the National Health and Nutrition Examination Survey III (NHANES), which applies a minor adjustment to the NCEP: ATP criteria, determined that 10% of children and adolescents aged 12 to 19 years old presented MetS in the United States. Later efforts took advantage of the fact that abdominal obesity is a predictor of IR, widely employing this variable to diagnose MetS; nevertheless, some research suggested that waist circumference alone is not a suitable predictor of metabolic risk in children and adolescents, making it critical to differentiate between MetS and obesity definitions; therefore, some young population-focused criteria were standardized for appropriate and early diagnosis.

In this respect, the International Diabetes Federation (IDF) definition constituted the most accepted (Figure 2), establishing that from 10 to 16 years old, abdominal obesity plus the presence of at least two other components must be considered to diagnose MetS. Between 6 and 10 years old, MetS is not diagnosed, but abdominal obesity must be taken care of (Zimmet et al., 2007). However, in this definition, the cut-off values for serum parameters are based on adult data due to the lack of normative values for the young population (D'Adamo et al., 2011). Accordingly, in 2014, the IDEFICS study (Identification and prevention of Dietary-and lifestyle-induced health Effects in Children and infantS) introduced an improved criterion to diagnose MetS in prepubertal children by establishing a MetS score based on the sum of age and gender-specific percentiles for dyslipidemia, HOMA index, waist circumference and mean arterial pressure Z-scores, as presented in Figure 2 (Ahrens et al., 2014; Börnhorst et al., 2019).

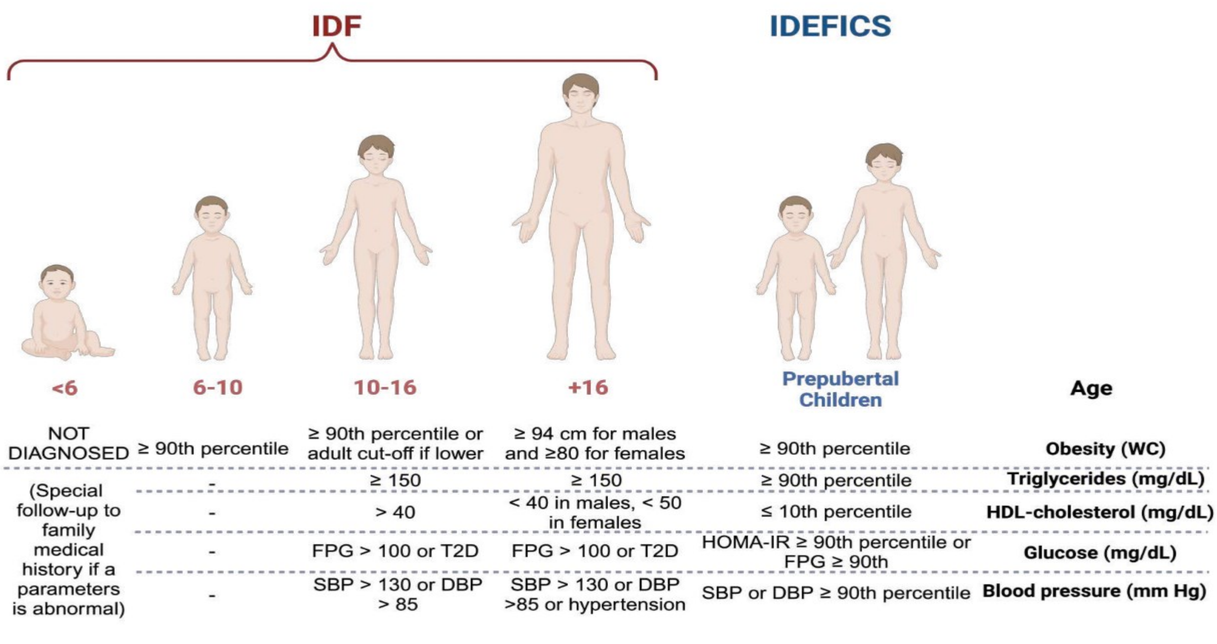

Figure 2. IDF and IDEFICS MetS definitions comparison. Definition of the International Diabetes Federation (IDF) of MetS based on age classification in babies less than six years old (<6), kids from six to ten years old (6-10), teenagers from ten to sixteen years old (10-16), and adolescents from sixteen to eighteen years old (+16); compared to the Identification and prevention of Dietary-and lifestyle-induced health Effects in Children and infantS (IDEFICS) definition based on percentiles. DBP: diastolic blood pressure; FPG: Fasting plasma glucose; HDL: high-density lipoprotein; HOMA-IR: insulin resistance homeostatic model assessment; SBP: systolic blood pressure; T2D: Type 2 diabetes mellitus; WC: waist circumference.(Ahrens et al., 2014; Zimmet et al., 2007) Created with BioRender.com.

Metabolic Adaptations to Exercise

Exercise is classified based on the type of physical activity performed in endurance (aerobic) and resistance (strength). Endurance exercise is defined as a long-duration activity executed at a relatively low intensity, while resistance exercise is defined as a short-duration activity executed at a relatively high intensity. Energy for anaerobic high-intensity exercise derives from ATP-phosphocreatine and glycogen stores. In contrast, aerobic moderate-to-low-intensity exercise uses glycogen and triacylglycerols depending on the duration and intensity of the activity. Several metabolic responses are promptly activated after physical activity begins, inducing disturbances on cellular homeostasis promoted by a transient increase in the secretion of stress hormones such as cortisol and catecholamines, causing increased blood flow, heart, and respiratory rate to sustain the oxygen and substrate demand on muscles, also activating several enzymes involved in fatty acids and glucose oxidation pathways (Lambert, 2016).

While responses are temporary, constant exercise repetition leads to adaptations such as tissue remodeling or altered regulation. Endurance/aerobic training is associated with improved blood flow, cardiac output, maximal oxygen consumption, and mitochondrial biogenesis. In contrast, strength/anaerobic exercise is related to increases in muscle size, as well as muscle remodeling due to a change in fiber proportion, although these adaptions depend on some aspects, such as the volume and intensity of the training (Liu et al., 2020). For instance, associated with high-intensity interval training programs (HIT), which is a type of strength exercise, there is a downregulation of phosphagen and carbohydrate metabolism in favor of lipid oxidation after training, as well as an increased skeletal muscle oxidative capacity (Gibala & Mcgee, 2008).

Also, cardiac remodeling is induced as a response to chronic exercise. This remodeling consists of physiological heart hypertrophy, which enhances contractile function and improves mitochondrial energetic metabolism (Seo et al., 2020). Adaptations also include white adipose tissue cell hypotrophy, decrease in lipid content, and mitochondrial biogenesis, as well as overexpression of some adipokines such as leptin, adiponectin, IL-6, and TNFα (Stanford et al., 2015).

Metabolic adaptations to exercise in children and adolescents

Physiological adaptations to exercise in children and adolescents cannot be evaluated under the same criteria as those for adults, considering that several body systems present some undeveloped characteristics at a younger age (Figure 3). Besides, it is essential to differentiate between the physiological adaptations from growth and maturity and those applicable to physical activity practice. For instance, at a younger age, the proportion, size, and recruitment of type I muscle fibers are more significant, determining the predominance of aerobic energy metabolism (Dotan et al., 2012). In this sense, children have a greater recovery capacity associated with diminished lactate production. Also, the intramuscular reserve of glycogen and PC is lower compared to adults, while the activity of enzymes related to the Krebs cycle is elevated (Kaczor et al., 2005).

Some hormones that directly regulate exercise metabolism include catecholamines, insulin, growth hormones, insulin-like growth factors, and steroid sex hormones, so it is evident that exercise responses and adaptations have other implications for children and adolescents. Actually, they cannot be classified as a single group since their biological maturation is manifested by hormonal production, body mass, and composition differences, which determine several physical capacities (Leite De Prado et al., 2006).

Concerning cardiovascular physiology, in maximal and submaximal exercise, children present higher heart rates despite the diminished catecholaminergic signaling associated with the reduced stroke volume and cardiac output due to the smaller size of the heart and blood volume compared to adults (Rowland et al., 2000). The latter correlates with a higher respiratory rate; however, as the child grows, the respiratory system gradually enhances several ventilatory parameters such as tidal volume, minute ventilation, total lung capacity, and maximal expiratory ventilation, adjusting the respiratory rate both in submaximal and maximal exercise (Dotan et al., 2012; Leite De Prado et al., 2006).

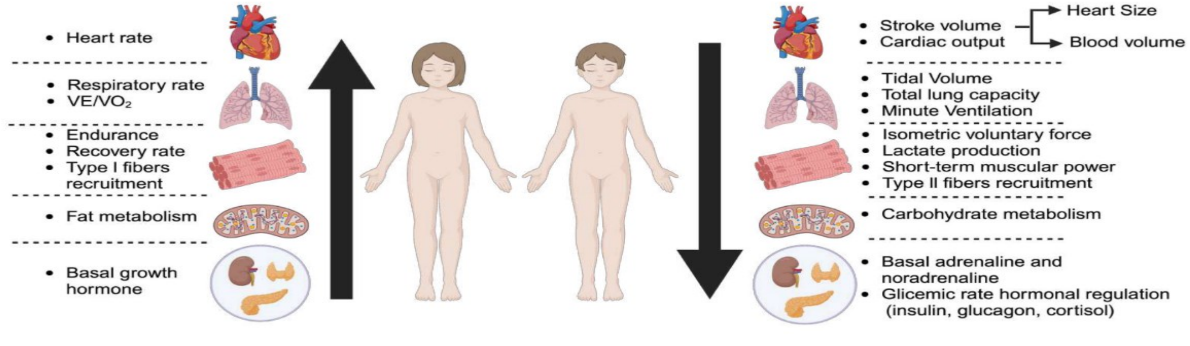

Figure 3. Metabolic and physiological parameters associated with physical activity in children compared to adults. The graphic presents the cardiovascular, respiratory, muscular, mitochondrial, and hormonal features of children and adolescents that differ from the mean levels established for the adult population. Higher values of the parameters than adults are represented next to the up-arrow (left side), while lower values of the parameters are represented next to the down-arrow (right side). VE/VO_2: ventilatory equivalent for oxygen.(Dotan et al., 2012; Leite De Prado et al., 2006) Created with BioRender.com.

MetS and Endurance Exercise

Children exhibiting insufficient physical activity and low aerobic fitness are more likely to present MetS as adolescents (McMurray et al., 2008). However, the beneficial effects of endurance exercise on metabolic health for patients with obesity, MetS, and T2D have mainly been studied in the older population, considering those are the primary sufferers of these diseases. In this regard, several studies have demonstrated the efficacy of simple routines like daily 30-minute walking and more structured exercise routines such as High-Intensity Interval Training (HIIT) workouts in ameliorating several physical and metabolic parameters of obese and MetS patients over 50 years. In fact, HIIT interventions have been widely associated with improving other inflammatory markers like adiponectin, leptin, and TNF-α in MetS patients (Khalafi & Symonds, 2020). However, a short detraining period reverts the beneficial effects on the pro-inflammatory state; thus, physical activity must be continuous to relieve the MetS disturbances caused by cytokines such as IL-1β, IL-6, TNF-α, and INF-γ (Steckling et al., 2016). Interestingly, HIIT did not show superior effects compared to moderate-intensity training in reducing metabolic parameters like total cholesterol, triglycerides, and serum glucose levels in children with metabolic disorders. However, both exercise intensities contribute to improving cardiometabolic health (Cao et al., 2022).

MetS and Resistance Exercise

Most studies on resistance training are directed to sarcopenia-associated health impairment in older adults. However, besides low muscular tone and general weakness, sarcopenia has also been associated with an increased risk of developing metabolic pathologies by impairing body composition through increased fat mass over the muscle mass ratio. For instance, low skeletal muscle mass percentage is closely associated with MetS emergence, so an increase in relative skeletal muscle mass can prevent this risk. In this regard, several studies have demonstrated that resistance exercise could reduce the fat mass content with a concomitant increase in muscle mass, thus not affecting total body mass and increasing the resting metabolic rate due to elevated muscle protein turnover. Interestingly, the fat mass reduction due to resistance training does not significantly affect the lipid profile. However, it has been associated with glucose and insulin response improvement, moderating MetS consequences (Strasser et al., 2010).

Furthermore, when skeletal muscle is strengthened through exercise, MetS incidence diminishes in adult men regardless of age and body size (Jurca et al., 2005). Actually, in adolescent girls, it was proved that poor performance on strength tests is directly associated with obesity and metabolic risk (Mota et al., 2010).

Table 1 summarizes some reports on the cardiometabolic outcomes of physical activity in children and adolescents with obesity and signs of MetS. Reports demonstrate the effectiveness of physical activity in reducing the risk of developing MetS and ameliorating several MetS manifested in overweight and obese children and adolescents. The primary noticeable outcomes of exercise interventions were on body composition (particularly on fat mass and/or visceral fat percentage loss) and aerobic power improvement, where the combination of resistance and endurance training was more efficient. Interestingly, lifestyle interventions result in more significant benefits in cardiometabolic markers (apolipoproteins, lipid profile, blood pressure) and hormonal regulation (ghrelin, leptin, adiponectin) than physical activity interventions alone, by including specific nutritional advice sessions, psychological therapy, anti-screen-time recommendations and guidance for the whole family. Although less effective on cardiometabolic components improvement, the importance of school-based interventions should not be overlooked, given its relevance to general obesity risk prevention (Chen et al., 2006; Davis et al., 2009, 2011; de Mello et al., 2011; Kelishadi et al., 2008; Li et al., 2014; Pedrosa et al., 2011; Reinehr et al., 2009).

Table 1
Cardiometabolic outcomes of different physical activity interventions in children and adolescents with obesity and signs of MetS.

Participants	Physical activity intervention (PAI)	Evaluated Parameters	Metabolic Outcome
15-year-old overweight and obese adolescents (Davis et al., 2011).	CT intervention: 90 minutes of combined aerobic and strength training per session. 2 sessions per week for 16 weeks. * Behavioral therapy.	Anthropometry, Cardiorespiratory fitness Dietary intake Serum glucose, Serum insulin.	↑ Fitness ↓ Waist circumference ↓ Fasting insulin ↓ Visceral fat.
15-year-old overweight adolescents (Davis et al., 2009).	CAST intervention: 60 minutes of combined exercise training per session. 2 sessions per week for 16 weeks. * Nutritional advice.	Anthropometry, Serum glucose, Serum insulin.	↓ BMI ↓ Fat mass ↓ Glucose.
15- to 19-year-old adolescents diagnosed with MetS (de Mello et al., 2011).	AT+RT intervention: 30 minutes of AT plus 30 minutes of RT per session. 3 sessions per week for 1 year.	Anthropometry, Serum lipids, Serum glucose, HOMA-IR, Adiponectin.	↓ BMI levels ↓ Fat mass ↓ Visceral fat ↓ total cholesterol ↓ Fasting glucose ↓ Waist circumference ↑ Adiponectin.
LIFESTYLE INTERVENTION			
7- to 9-year-old overweight and obese children (Pedrosa et al., 2011).	Nutritional advice, Screentime reduction, and physical activity promotion.	Anthropometry, Blood pressure, Serum glucose,	↓ BMI ↓ Waist-to-height ratio.

		Serum lipids, Apolipoproteins.	↓ Triglycerides ↓ HDL-c ↓ ApoA-1, ApoB ↓ MetS prevalence.
10- to 16-year-old obese children and adolescents (Reinehr et al., 2009).	Nutritional advice, psychological therapy, and AT once a week. * 1 year follow-up.	Anthropometry, Serum glucose, Serum lipids, Blood pressure.	↓ BMI levels ↓ oGTT ↓ Blood pressure ↓ Waist circumference ↓ MetS prevalence.
10- to 17-year-old children and adolescents (Chen et al., 2006).	High-fiber, Low-fat diet, and daily aerobic exercise (2 hours per day, gym-based exercises and tennis mainly). * 2 week follow up.	Insulin, HOMA-IR, Anthropometry, Serum lipids, Serum glucose, Blood pressure.	↓ Body weight ↓ HOMA-IR ↓ Insulin ↓ Triglycerides ↓ HDL-c ↓ total cholesterol ↓ Blood pressure ↓ MetS prevalence.
SCHOOL-BASED INTERVENTION			
7- to 9-year-old obese children (Kelishadi et al., 2008).	40 minutes of AT, 5 sessions per week for 6 months. * 1 year follow-up.	Anthropometry, Serum glucose, Serum lipids, Blood pressure.	↓ BMI levels ↑ Ghrelin ↓ total cholesterol ↓ Leptin.
7- to 15-year-old children and adolescents (Li et al., 2014).	Multi-component PAI (rope and long jumping, endurance running, and basketball). * 12 weeks follow-up. * 3 PE lessons per week of 45 minutes, with at least 30 minutes of moderate to vigorous PA in each class.	Anthropometry, Serum glucose, Serum lipids, Waist Circumference.	↓ BMI levels ↓ Fasting glucose.

ApoA-1: Apolipoprotein A-1; ApoB: Apolipoprotein B; AT: aerobic training; BMI: body mass index; CAST: combination of strength and aerobic training; CT: circuit training; HOMA-IR: homeostasis model assessment for insulin resistance; oGTT: oral glucose tolerance tests; PA: physical activity; PE: physical education; RT: resistance training; ST: strength training.

Discussion

Technological advances have improved quality of life in different ways; however, this progress has impacted how much movement a person must do to complete basic chores. In this sense, sedentarism keeps rising worldwide, so it is critical to promote physical activity, particularly among the young population, considering the relevance of behavior patterns established at this stage of life. The evidence demonstrates that the time spent on physical activity decreases as one ages, which correlates with increased obesity prevalence (Ortiz-Sánchez et al., 2021).

Sociocultural aspects also influence sedentary behavior; at least half the population lives in urban areas where public spaces to exercise are scarce and where just a small number of children and adolescents walk to their schools. In this regard, children living in marginalized zones with less access to natural outdoor spaces exhibit lower levels of physical activity and less cardiopulmonary aptitude in comparison to those children coming from zones with fewer social barriers. Likewise, parental influence is essential, so children of physically active parents show a greater probability of being physically active than those with sedentary parents (Rodríguez-Núñez et al., 2022; Yang et al., 1996). Furthermore, urban children and adolescents are more likely to have electronic devices that limit movement opportunities, raise the number of sitting hours per day, and induce "distraction feeding" behaviors, commonly resulting in increased energy intake by eating unconsciously (Braude & Stevenson, 2014).

Children spend a considerable part of their day at school. Hence, awareness of healthy lifestyles should be encouraged within classrooms and reinforced through physical education spaces to counter sedentary behavior (Brittin et al., 2017; De Araújo et al., 2023; Leiss & Kim, 2022). Unfortunately, physical education hours per week are severely compromised against other academic subjects in several schools, and they are not even mandatory in some curricula (Mckenzie & Lounsbery, 2009). Furthermore, some physical education lessons do not achieve moderate to vigorous intensity for at least 50% of the session, which is necessary to achieve the benefits of physical activity (Hall López et al., 2016).

Future Directions

Although many reports relate sedentary behavior health detriment and MetS emergence, some evidence gaps in the younger group persist; thus, these must be prioritized to inform future guidelines. For instance, most current studies overlook the fact that MetS often coexists with other conditions, such as obesity, hypertension, and IR. By encompassing it, the understanding of the underlying molecular and physiological mechanisms by which exercise improves metabolic health in youth will be elucidated, optimizing the intervention strategies.

MetS prevalence varies in relation to racial and ethnic background since childhood, as well as the predominant MetS signs indicating a different pathophysiological origin (Walker et al., 2012; Zhang et al., 2022). Therefore, one of the topics that must be deeply acknowledged is the ethnic and racial diversity of the populations studied. In this matter, most of the reports involved Caucasian children and adolescents; thus, future research should aim to include diverse populations to assess potential disparities in response to exercise interventions. Also, due to the genetic component of MetS emergence, detailed family-based interventions should be studied, which involve not only the parents in physical activity promotion but also compel them to make lifestyle changes to explore the outcomes in terms of the efficacy of the exercise.

As previously mentioned, technology is usually referred to as an impediment to a physically active lifestyle and a sedentary inducer. However, several digital health-related technologies have been launched nowadays, so there is considerable potential to leverage mobile apps, wearable devices, virtual reality platforms, and video games to design exercise interventions for children and adolescents with MetS. Although some research on this matter has already been developed, an in-depth assessment of the effectiveness and suitability of these technologies is needed, given the variability in the types of devices, the intensity cut points, the analytical methods performed, and the data recollected by each one (DiPietro et al., 2020). By addressing these gaps, future research can advance our understanding of exercise's role in managing MetS in children and adolescents, ultimately contributing to more effective prevention and treatment strategies.

In summary, solid evidence in this age group is scarce, and beyond seeking palliative treatments, it is more important to insist on the prevention of metabolic diseases in children and adolescents. A fundamental strategy must be establishing programs promoting physical activation among the young population. However, it should be recognized that the programs' planning, implementation, and impact are not a short-term solution (Medina-Blanco et al., 2011). Motivation to practice physical activity as a preventive measure must be encouraged, accompanied by a greater relevance of physical education in schools and home accompaniment focused on strategies like a balanced diet and screen time reduction.

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