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Review

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What Is the Role of Resistance Exercise in Improving the Cardiometabolic Health of Adolescents with Obesity?

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Traditionally, individuals with obesity have been encouraged to participate in aerobic exercise for long-term weight management and improved obesity-related health outcomes. Recently, resistance exercise has become a popular mode of exercise among youth with obesity. However, to date, the literature is mixed as to whether resistance exercise training alone improves body weight, fat free mass, body composition, cardiovascular risk factors, or atherogenic lipoprotein profiles. The limited research in this area suggests potential sex differences in response to resistance training in youth. The literature is more consistent in demonstrating improvements in muscular fitness and insulin resistance independent of caloric restriction and weight loss. Although major health organizations recommend combining aerobic and resistance training, little research has examined the effects of their combination versus their individual effects, thus it is unclear whether their combination is associated with benefits that extend beyond those of either exercise modality alone. The purpose of this review is to examine the effects of resistance exercise on body composition and the health risk factors associated with cardiovascular disease and type 2 diabetes in youth with obesity.

Key words: Childhood obesity, Resistance exercise, Abdominal adiposity, Insulin resistance, Cardiovascular disease risk

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INTRODUCTION

According to the World Health Organization[1], the number of children and adolescents with obesity has increased from 11 million to 124 million during the past four decades. Although variations in the prevalence of childhood obesity exist across countries[1], it is now apparent that childhood obesity is a major public health concern worldwide.

It is well documented that children and adolescents with obesity are more likely than normal-weight children and adolescents to have obesity in adulthood[2,3], with a heightened risk of developing hypertension, dyslipidemia, insulin resistance, type 2 diabetes, and non-alcoholic fatty liver disease.[4-8] Of particular health concern is an increase in waist circumference in children and adolescents over time[9] since enlarged waist circumferences indicate increased visceral adiposity and is associated with numerous cardiometabolic risk factors independent of body mass index (BMI).[10-12]

Previous studies have demonstrated that cardiorespiratory fitness (CRF) protects against obesity-related comorbid conditions in children.[13-16] Emerging evidence also suggests that muscular strength, another main component of health-related physical fitness, is an important factor in the prevention of chronic health conditions.[17] In adults, muscular strength is inversely associated with all-cause-, cancer-, and cardiovascular disease (CVD)-related mortality independent of BMI and CRF.[18,19] In children and adolescents, evidence suggests that muscular strength measured by a 1-repetition maximum (1-RM) or hand grip strength test is associated with lower insulin resistance and inflammatory biomarkers independent of CRF.[20,21] These findings support the current public physical activity guidelines that children and adolescents (age 6–17 years) should engage in muscle strengthening physical activity at least 3 days a week, in addition to regular aerobic physical activity.[22]

The purpose of this review is to examine the effects of resistance exercise training on abdominal fat, insulin resistance, and CVD risk factors in children and adolescents with obesity. Given that major health authorities (e.g., Public Health Agency of Canada, U.S. Department of Health and Human Services, World Health Organization) recommend a combination of resistance and aerobic exercise training, we also explore the effects of combining resistance and aerobic exercise on cardiometabolic risk factors in children and adolescents.

EFFECTS OF RESISTANCE EXERCISE ON BODY COMPOSITION

Lifestyle interventions to increase physical activity and promote a healthy diet have been the first-line approach for treating youth with obesity. Because childhood obesity is a strong predictor of adult morbidity and early mortality[23], early intervention is essential to prevent and reverse obesity-related risk factors in youth. Traditionally, adults with obesity have been encouraged to participate in aerobic exercise for long-term weight management. During the past decade, resistance exercise has also become a popular mode of exercise in youth with obesity, and some studies have demonstrated that engaging in resistance exercise improves muscular strength and lean body mass or skeletal muscle mass[24-26] and provides psychological benefits.[27,28]

Resistance exercise, both alone and combined with dietary interventions (e.g., reducing caloric restriction or sugar intake), has been examined for its effects on total and abdominal obesity in children and adolescents (Table 1). As shown in Table 1, most studies have used short-duration resistance exercise regimens (6–16 weeks); one study lasted 36 weeks.[29] Furthermore, most studies have used exercise durations of 40–60 minutes per session, 3 day/wk, and the vast majority of studies reported no significant weight loss following resistance training. For example, Shaibi et al.[24] examined the effects of a 16-week progressive resistance training program without caloric restriction (2 day/wk, 60 minutes per session, 10 single and multi-joint resistance exercises) on total fat measured using dual-energy X-ray absorptiometry (DXA) in a small sample of overweight Latino boys (BMI > 85th percentile). They observed no significant changes in body weight or total fat in the resistance exercise group, although significant increases in muscular strength (bench press and leg press 1-RM) and total lean body mass were found in the resistance exercise group compared with controls. Subsequently, the same research group[30] conducted a 16-week randomized controlled trial to compare the effects of resistance exercise training (2 day/wk, 60 minutes per session, whole-body resistance exercise) combined with a carbohydrate nutrition program (≤ 10% of total daily calorie intake from added sugar and consuming at least 14 g/1,000 kcal of dietary fiber/day) versus the carbohydrate nutrition program alone on changes in body composition and metabolic markers in 54 overweight Latino boys and girls (age 14–18 years). Although the resistance exercise combined with carbohydrate nutrition group showed significantly improved muscular strength (1-RM bench press) compared with the nutrition program alone and the control group, there were no significant resistance exercise training effects on changes in body weight, total fat mass, or fat free mass (FFM) in a mixed group of boys and girls.

To our knowledge, four randomized controlled trials[26,31-33] have examined changes in abdominal obesity (measured using waist circumference) in response to resistance exercise versus non-exercising controls, and three randomized controlled trials[26,32,33] have examined the effect of resistance versus aerobic exercise on visceral adiposity (Table 1). Of those, only one[26] demonstrated a significant reduction in waist circumference and visceral fat following resistance exercise training. Suh et al.[33] conducted a 12-week study of caloric restriction (>1,200 kcal/day to prevent malnutrition, limiting dietary fat intake and snacks) combined with either resistance exercise (3 day/wk, 60 minutes per session) or aerobic exercise (3 day/wk, 40 minutes per session) on total and visceral fat and metabolic markers in 30 overweight Korean boys and girls (BMI > 85th percentile; mean age, 13.1 years). Despite an intensive individualized diet education program (2 day/wk for 12 weeks), significant increases

Table 1. Effects of resistance exercise alone or combined with aerobic exercise on body weight and total and abdominal adiposity

Author (year)	Subject	Treatment	Average BMI (kg/m²)	Exercise prescription	Duration	ΔBW	ΔTFM	ΔWC	ΔVAT	ΔSAT	AT measure
Resistance exercise											
Benson et al. (2008)[31]	46 Boys, 32 girls (10–15 yr)	Control	21.9	No treatment	8 wk	2.0 kg	1.0 kg	0.5 cm			
		RE	23.2	2 day/wk, 11 exercises, 80% of peak strength, 2 sets, 8 reps		1.5 kg	0.2 kg*	–0.8 cm*			
Davis et al. (2009)[30]	28 Boys, 26 girls (14–18 yr)	Control	33.7	No treatment	16 wk	0.6 kg	–0.1 kg				
		NE	32.3	1 day/wk nutrition education (90 min)		0.1 kg	–0.1 kg				
		NE+RE	34.9	2 day/wk, 60 min/day, 10 whole-body RE		–0.3 kg	–1.3 kg				
Hasson et al. (2012)[34]	48 AA, 52 Latino (mean ± SD, 15.4 ± 1.1 yr)	Control	AA, 36.0; Latino, 33.9	No treatment	16 wk	No significant group differences in the changes in BW, TFM, VAT, or SAT					
		NE		1 day/wk nutrition education (90 min)							
		NE+RE		2 day/wk, 60 min/day, 10 whole-body RE							
Kelly et al. (2015)[35]	26 Boys (14–18 yr)	Control	34.2	No treatment	16 wk	–7.1 kg	–3.8 kg				
		RE	33.1	3 day/wk, 60 min/day; 1–4 wk: 1 set, 12 reps, 5–10 wk: 2–3 sets, 12 reps, 11–16 wk: 3–4 sets, 12 reps		5.9 kg	2.9 kg				
Lee et al. (2012)[26]	45 Boys (12–18 yr)	Control	33.9	No treatment	3 mon	2.6 kg	1.2 kg	1.1 cm	0.2 kg	0.2 kg	MRI
		AE	36.6	3 day/wk, 60 min/day, 60%–75% of VO_{2peak}		–0.04 kg*	–3.0 kg*	–2.0 cm*	–0.1 kg*	–0.5 kg*	
		RE	34.5	3 day/wk, 60 min/day, 10 exercises, >60% of 1 RM, 2 sets, 8–12 reps		–0.6 kg*	– 2.5 kg*	–3.2 cm*	–0.2 kg*	–0.4 kg*	
Lee et al. (2013)[32]	44 Girls (12–18 yr)	Control	35.3	No treatment	3 mon	0.1 kg	0.7 kg	–0.3 cm	5.9 cm²	–2.9 cm²	MRI
		AE	32.9	3 day/wk, 60 min/day, 60%–75% of VO_{2peak}		–1.3 kg	–2.4 kg	–2.5 cm	–15.7 cm²*	–7.8 cm²	
		RE	36.4	3 day/wk, 60 min/day, 10 exercises, >60% of 1 RM, 2 sets, 8–12 reps		–0.3 kg	–2.2 kg	–1.8 cm	–4.5 cm²	–14.4 cm²	
Shaibi et al. (2006)[24]	22 Boys (mean ± SD: control, 15.6 ± 0.5; RE, 15.1 ± 0.5)	Control	34.6	No treatment	16 wk	2.1 kg	–0.2 kg				
		RE	32.5	2 day/wk, 50 min/day, 10 exercises, 60%–97% of 1 RM, 1–3 sets, 8–15 reps		1.9 kg	–1.3 kg				
Suh et al. (2011)[33]	15 Boys, 15 girls (13.1 yr)	Diet only	27.1	2 day/wk diet education program	12 wk	1.8 kg†	0.9%†	1.6 cm†	3.3 cm²†		CT
		AE+diet	26.3	3 day/wk, 40 min/day, 60%–70% of VO_{2max}+ 2 day/wk diet education program		–0.6 kg	–0.3%	–0.8 cm	–0.9 cm²		
		RE+diet	25.3	3 day/wk, 60 min/day, 60% of 1 RM, 2–3 sets, 10–12 reps+2 day/wk diet education program		1.6 kg†	0.9%†	–0.1 cm	5.2 cm²†		
Sung et al. (2002)[36]	54 Boys, 28 girls (8–11 yr)	Control	24.6	Low energy diet (900–1,200 kcal/day) 75 min/session	6 wk	–0.1 kg	0.01 kg				
		RE	25.5	Low energy diet (900–1,200 kcal/day)+ 20 workout stations, 75%–100% of 10 RM		0.6 kg	–0.03 kg				
Yu et al. (2005)[29]	154 (8–11 yr)	Control+diet	24.7	Low energy diet (900–1,200 kcal/day)	36 wk	5.3 kg†	1.5 kg†				
		RE+diet	25.5	1–6 wk: diet+3 day/wk, 75 min/day, 9 exercises, 75% of 10 RM, 1 set, 20 reps; 7–32 wk: diet+ 1 day/wk, 60 min/day, 8–9 exercises, 2–3 sets, 10–20 reps		6.1 kg†	0.8 kg†				

(*Continued to the next page*)

Table 1. Continued

Author (year)	Subject	Treatment	Average BMI (kg/m^2)	Exercise prescription	Duration	ΔBW	ΔTFM	ΔWC	ΔVAT	ΔSAT	AT measure
Resistance+aerobic exercise											
Ackel-D'Elia et al. (2014)[37]	22 Boys, 50 girls (15–19 yr)	LPA	34.6	3 day/wk, 60 min/day, recreational team sports, gymnastics, walking	6 mon	–0.5 kg	–1.1 kg				
		AE	35.1	3 day/wk, 60 min/day, treadmill		–5.7 kg†	–3.0 kg†				
		AE+RE	35.1	3 day/wk, 60 min/day, 30 min AE+30 min RE, 10 exercises, 3 sets, 6–20 reps		–8.1 kg*,†	–9.8 kg*,†				
Bharath et al. (2018)[38]	40 Girls (mean ± SD, 14.7 ± 1 yr)	Control	30.0	No treatment	12 wk	0.2 kg	–0.4%	0.5 cm			
		AE+RE	30.0	3 day/wk, 60 min/day, 30 min AE, 40%–70% of HRR+20 min RE, 10 band exercises, 15–20 reps		–6.2 kg*,†	–3.4%*,†	–4.1 cm*,†			
Dâmaso et al. (2014)[39]	139 (15–19 yr)	AE	35.7	3 day/wk, 60 min/day, 50%–70% of VO_{2peak}	1 yr	–8.8 kg†	–8.1 kg†		–1.4 cm†	–0.5 cm†	Ultrasound
		AE+RE	36.7	3 day/wk, 60 min/day, 30 min AE+30 min RE, 6–20 RM, 3 sets		–12.3 kg†	–14.2 kg*,†		–1.6 cm*,†	–0.9 cm*,†	
Davis et al. (2009)[40]	41 Girls (mean ± SD, 15.2 ± 1.1 yr)	Control	34.6	No treatment	16 wk	–0.3 kg	0.4 kg				
		NE	33.8	1 day/wk nutrition education (90 min)		0.3 kg	–0.1 kg				
		NE+RE	32.8	2 day/wk, 60 min/day, 10 whole-body RE		2.4 kg*	0.6 kg*				
		NE+AE+RE	33.6	2 day/wk, 60 min/day, 30 min AE+30 min RE		–0.8 kg*	–1.4 kg*				
Davis et al. (2011)[41]	38 Girls (14–18 yr)	Control	36.4	No treatment	16 wk			3%	6.0%†	8.0%†	MRI
		AE+RE	32.4	2 day/wk, 60–90 min/day, 30–45 min AE (70%–85% of HR_{max})+30–45 min RE, 2 sets, 8–12 reps				–3%*	–10.0%*,†	–10.0%*,†	
		AE+RE+MI	34.6	2 day/wk, 60–90 min/day, AE+RE+MI: 4 individual and 4 group sessions				NA	NA	NA	
de Piano et al. (2012)[42]	27 Boys, 31 girls (15–19 yr)	AE (no NAFLD)	33.5	3 day/wk, 60 min/day, 50%–70% of VO_{2peak}	12 mon	–9.4 kg†	–6.7 kg†		–1.4 cm	–1.1 cm	Ultrasound
		AE (with NAFLD)	38.0	3 day/wk, 60 min/day, 50%–70% of VO_{2peak}		–10.9 kg†	–10.2 kg†		–2.6 cm†	–0.2 cm	
		AE+RE (no NAFLD)	36.5	3 day/wk, 60 min/day, 30 min AE+30 min RE, 3 sets, 6–20 reps		–12.0 kg†	–14.1 kg*,†		–1.8 cm	–0.8 cm	
		AE+RE (with NAFLD)	38.4	3 day/wk, 60 min/day, 30 min AE+30 min RE, 3 sets, 6–20 reps		–14.5 kg†	–15.4 kg†		–1.9 cm	–0.8 cm*,†	
Farpour-Lambert et al. (2009)[43]	16 Boys, 28 girls (6–11 yr)	Control	25.1	No treatment	3 mon	1.6 kg†	0.8%†		0.7%†		DXA
		AE+RE	25.4	3 day/wk, 60 min/day, 30 min AE, 55%–65% of VO_{2max}+20 min RE+10 min stretching		1.0 kg†	–1.5%*,†		–2.1%*,† (Abdominal %fat)		
Foschini et al. (2010)[44]	15 Boys, 17 girls (mean ± SD, 16.5 ± 1.7 yr)	AE+RE (LP)	36.5	3 day/wk, 60 min/day, 30 min AE+30 min RE, 6–20 RM, 3 sets	14 wk	–8.6 kg†	–9.7 kg†		–1.5 cm†	–0.5 cm†	Ultrasound
		AE+RE (DUP)	37.7	3 day/wk, 60 min/day, 30 min AE+30 min RE, 3 sets (day 1: 15–20 RM, day 2: 10–12 RM, day 3: 6–8 RM)		–10.7 kg†	–12.2 kg†		–1.2 cm†	–0.3 cm†	

(*Continued to the next page*)

Table 1. Continued

Author (year)	Subject	Treatment	Average BMI (kg/m^2)	Exercise prescription	Duration	ΔBW	ΔTFM	ΔWC	ΔVAT	ΔSAT	AT measure
Inoue et al. (2015)[45]	17 Boys, 28 girls (15–18 yr)	AE	35.1	3 day/wk, 60 min/day; 1–13 wk: AE only, 14–26 wk: 30 min AE+30 min RE, >75% of 1 RM, 3 sets	1 yr	–9.1 kg†	–7.5 kg†		–1.9 cm†		Ultrasound
		AE+RE (LP)	36.4	3 day/wk, 60 min/day, 30 min AE+30 min RE, 6–20 RM, 3 sets		–10.9 kg†	–12.4 kg†		–1.9 cm†		
		AE+RE (DUP)	38.2	3 day/wk, 60 min/day, 30 min AE+30 min RE, 3 sets (day 1: 15–20 RM, day 2: 10–12 RM, day 3: 6–8 RM)		–16.4 kg†	–17.9 kg*,†		–2.0 cm†		
Lee et al. (2019)[46]	42 Boys, 76 girls (12–17 yr)	AE	33.7	3 day/wk, 60 min/day, 50%–65% of VO$_{2peak}$	6 mon	–4.0 kg†,‡	–3.7 kg†,‡	–3.2 cm†			
		RE	33.4	3 day/wk, 60 min/day, 8 exercises (plus push-ups and sit-ups), 2 sets, 12–15 reps		–1.1 kg	–2.1 kg	–1.6 cm			
		AE+RE	32.3	3 day/wk, 60 min/day (30 min AE+30 min RE)		1.0 kg†	–0.9 kg	–1.6 cm			
Monteiro et al. (2015)[47]	27 Boys, 21 girls (11–17 yr)	Control	31.0	No treatment	20 wk	2.6 kg†	1.3 kg	2.5 cm†	0.01 cm†	–0.09 cm	Ultrasound
		AE	30.2	3 day/wk, 50 min/day, 65%–85% of VO$_{2peak}$		–1.1 kg†	–3.1 kg	–4.2 cm†	–0.82 cm†	–0.14 cm	
		AE+RE	33.2	3 day/wk, 60 min/day, 30 min AE+30 min RE, 55%–75% of 1 RM, 1–2 sets, 12–20 reps		–0.2 kg†	–2.6 kg	–3.8 cm†	–0.06 cm	0.13 cm	
Sigal et al. (2014)[48] & Alberga et al. (2015)[49]	91 Boys, 213 girls (14–18 yr)	Control	34.1	Diet: energy deficit 250 kcal/day,	26 wk	1.3 kg	0.4 kg	–0.2 cm	–0.9 cm^2	5.6 cm^2	MRI
		AE	34.7	Diet+20–40 min/day, 65%–85% of HR$_{max}$, 4 day/wk		–0.1 kg	–1.2 kg	–3.0 cm*,†	–0.2 cm^2	–16.2 cm^{2*,†}	
		RE	35.1	Diet+7 whole-body exercises, 2–3 sets, 8–15 reps, 4 day/wk		0.3 kg	–1.3 kg†	–2.2 cm*,†	–4.0 cm^2	–22.7 cm^{2*,†}	
		AE+RE	34.6	Diet+full AE+RE above, 4 day/wk		–0.8 kg	–1.7 kg†	–4.1 cm†	–3.9 cm^2	–18.7 cm^{2*,†}	
Woo et al. (2004)[50]	54 Boys, 28 girls (9–12 yr)	Diet only	24.5	Low energy diet (900–1,200 kcal)	6 wk	0.6 kg	–0.3%				
		Diet+AE+RE	25.4	Low energy diet+2 day/wk, 75 min/day AE, 18 workout stations, 60%–70% of HR$_{max}$+ 30 min RE		0.6 kg	–0.6%				
		After 6 wk									
		Diet only	24.7	Low energy diet (900–1,200 kcal)	1 yr	–0.2 kg/m^2	–1.3%				
		Detraining	26.1	2–mon diet monitoring program		0.0 kg/m^2	2.1%				
		Continued training	25.3	Weekly exercise program		0.1 kg/m^2	–4.9%†				

*Significantly different from the control or other groups (vs. RE or AE+RE), $P<0.05$; †Significantly different from baseline within group, $P<0.05$; ‡Significantly different from the combined group, $P<0.05$.

BMI, body mass index; Δ, change score; BW, body weight; TFM, total fat mass; WC, waist circumference; VAT, visceral adipose tissue; SAT, subcutaneous adipose tissue; AT, adipose tissue; RE, resistance exercise, reps, repetitions; NE, nutrition education; SD, standard deviation; AA, African-American; AE, aerobic exercise; VO$_{2peak}$, peak oxygen uptake; 1-RM, 1-repetition maximum; MRI, magnetic resonance imaging; VO$_{2max}$, maximum oxygen consumption; CT, computed tomography; LPA, leisure physical activity; HRR, heart rate reserve; MI, motivational interview; HR$_{max}$, heart rate max; NA, not available; NAFLD, nonalcoholic fatty liver disease; DXA, dual-energy X-ray absorptiometry; LP, linear periodization; DUP, daily undulating periodization.

in body weight, BMI, % body fat, and visceral fat were observed in the diet only and diet plus resistance exercise groups, but not in the diet plus aerobic exercise group. Thus, it appears that resistance exercise could be inferior to aerobic exercise at reducing visceral fat in overweight Asian adolescents.

Lee et al.[26,32] conducted two randomized controlled trials to examine the effects of 3 months of resistance exercise versus aerobic exercise (no caloric restriction) on total fat and regional body fat distribution using the gold standard, whole-body magnetic resonance imaging (MRI), in adolescent boys[26] and girls[32] with obesity (BMI >95th percentile, age 12–18 years). In those studies[26,32], both boys and girls participated in identical aerobic and resistance exercise regimens; those who were randomized to the resistance exercise group performed one to two sets with 8–12 repetitions of eight whole-body progressive resistance exercises until volitional fatigue for 3 day/wk at 60 minutes per session plus a single set of push-ups and sit-ups, and those who were randomized to the aerobic exercise group performed moderate intensity (60%–75% of peak oxygen uptake [VO_{2peak}]) aerobic exercise using treadmills and ellipticals for 3 day/wk at 60 minutes per session. Following the interventions, no significant weight loss was observed in any exercise group in either boys or girls. However, compared with the non-exercising controls, significant reductions in % body fat (resistance, –2.5% vs. aerobic, –2.6%), waist circumference (resistance, –3.2 cm vs. aerobic, –2.0 cm), visceral fat (resistance, –0.2 kg vs. aerobic, –0.1 kg), abdominal subcutaneous fat (resistance, –0.4 kg, vs. aerobic, –0.5 kg), and liver fat (resistance, –2.0% vs. aerobic, –1.9%) were observed in response to both aerobic and resistance exercise training in boys, whereas in girls, reductions in visceral and liver fat were observed in response to only aerobic exercise. Furthermore, unlike the significant increases in skeletal muscle mass that occurred in response to resistance exercise in boys, adolescent girls did not have increases in skeletal muscle mass after 3 months of resistance exercise training. Given the similar exercise training regimens, MRI methodology, and high exercise attendance rates (boys, 99% and girls, 97%), we are uncertain about the causes of the sex differences in response to resistance exercise training. It is possible that increased androgen levels in adolescent boys allowed them to have greater hypertrophy in response to resistance exercise.

To date, the effects of resistance exercise on body composition have been inconsistent between studies, and it is currently uncertain whether engaging in resistance training alone is associated with reductions in abdominal fat in youth with obesity. The inconsistency could result from the different body composition methodologies used between studies, which varied from simple field methods (e.g., bioelectrical impedance analysis) to sophisticated imaging modalities (e.g., DXA, MRI, computed tomography [CT]). In the pediatric literature, only four studies[26,32-34] out of ten[24,26,29-36] randomized trials examining the effects of resistance exercise on abdominal fat used imaging modalities (e.g., MRI and CT). Among them, three[32-34] of the four[26,32-34] studies reported that resistance exercise did not significantly reduce abdominal fat, and one[26] reported that it did reduce abdominal fat. Furthermore, most previous studies[29-31,33,34,36] included both boys and girls together in the analyses and did not examine the influence of sex on changes in study outcomes. Interestingly, the one study[26] to report reductions in visceral fat with resistance training included only boys. Thus, there could be sex differences in the body composition changes associated with resistance exercise. Clearly, further randomized controlled trials with large sample sizes are required to examine the influence of sex.

EFFECTS OF RESISTANCE EXERCISE ON INSULIN SENSITIVITY AND GLUCOSE TOLERANCE

Insulin resistance has been proposed as the underlying mechanism for the development of metabolic dysfunction and type 2 diabetes in youth with obesity.[51,52] Insulin-resistant children and adolescents are more likely to have a cluster of metabolic abnormalities than their insulin-sensitive counterparts.[53] Although aerobic exercise has traditionally been recommended for children and adolescents with obesity, age-appropriate resistance exercise could improve musculoskeletal strength, cardiometabolic profiles, motor skills, and psychosocial well-being in youth.[54]

We are currently aware of eight randomized controlled trials[24,26,30-35] that examined the effects of resistance exercise training (alone or combined with dietary modification) on insulin sensitivity and glucose tolerance in youth with overweight or obesity (Table 2). Of those eight trials, three studies[24,26,35] were limited to adolescent boys. Although no studies reported significant weight loss, three of

Table 2. Effects of resistance exercise alone or combined with aerobic exercise on insulin sensitivity and glucose tolerance

Author (year)	Subject	Treatment	Average BMI (kg/m^2)	Exercise prescription	Duration	ΔInsulin resistance	Measure
Resistance exercise							
Benson et al. (2008)[31]	46 Boys, 32 girls (10–15 yr)	Control	21.9	No treatment	8 wk	0.2	HOMA-IR
		RE	23.2	2 day/wk, 11 exercises, 80% of peak strength, 2 sets, 8 reps		0.1	
Davis et al. (2009)[30]	28 Boys, 26 girls (14–18 yr)	Control	33.7	No treatment	16 wk	$0.1\times10^{-4}\text{min}^{-1}$/μU/mL	FSIVGTT
		NE	32.3	1 day/wk nutrition education (90 min)		$0.2\times10^{-4}\text{min}^{-1}$/μU/mL	
		NE+RE	34.9	2 day/wk, 60 min/day, 10 whole-body RE		$0.0\times10^{-4}\text{min}^{-1}$/μU/mL	
Hasson et al. (2012)[34]	48 AA, 52 Latino (mean ± SD, 15.4 ± 1.1 yr)	Control	AA, 36.0; Latino, 33.9	No treatment	16 wk	AA: $-0.4\times10^{-4}\text{min}^{-1}$/μU/mL Latino: $-0.4\times10^{-4}\text{min}^{-1}$/μU/mL	FSIVGTT
		NE		1 day/wk nutrition education (90 min)		AA: $0.1\times10^{-4}\text{min}^{-1}$/μU/m* Latino: $0.3\times10^{-4}\text{min}^{-1}$/μU/mL*	
		NE+RE		2 day/wk, 60 min/day, 10 whole-body RE		AA: $0.0\times10^{-4}\text{min}^{-1}$/μU/mL Latino: $-0.2\times10^{-4}\text{min}^{-1}$/μU/mL	
Kelly et al. (2015)[35]	26 Boys (14–18 yr)	Control	34.2	No treatment	16 wk	$0.4\times10^{-4}\text{min}^{-1}$/μU/mL	FSIVGTT
		RE	33.1	3 day/wk, 60 min/day; 1–4 wk: 1 set 12 reps, 5–10 wk: 2–3 sets, 12 reps, 11–16 wk: 3–4 sets, 12 reps		$-0.6\times10^{-4}\text{min}^{-1}$/μU/mL	
Lee et al. (2012)[26]	45 Boys (12–18 yr)	Control	33.9	No treatment	3 mon	–0.1 mg/kg/min/μU/mL	Euglycemic clamp
		AE	36.6	3 day/wk, 60 min/day, 60%–75% of VO_{2peak}		0.4 mg/kg/min/μU/mL	
		RE	34.5	3 day/wk, 60 min/day, 10 exercises, > 60% of 1 RM, 2 sets, 8–12 reps		0.8 mg/kg/min/μU/mL*	
Lee et al. (2013)[32]	44 Girls (12–18 yr)	Control	35.3	No treatment	3 mon	–0.5 mg/kg/min/μU/mL	Euglycemic clamp
		AE	32.9	3 day/wk, 60 min/day, 60%–75% of VO_{2peak}		0.9 mg/kg/min/μU/mL*	
		RE	36.4	3 day/wk, 60 min/day, 10 exercises, > 60% of 1 RM, 2 sets, 8–12 reps		0.03 mg/kg/min/μU/mL	
Shaibi et al. (2006)[24]	22 Boys (mean ± SD: control, 15.6 ± 0.5; RE, 15.1 ± 0.5)	Control	34.6	No treatment	16 wk	$0.1\times10^{-4}\text{min}^{-1}$/μU/mL	FSIVGTT
		RE	32.5	2 day/wk, 50 min/day, 10 exercises, 60%–97% of 1 RM, 1–3 sets, 8–15 reps		$0.9\times10^{-4}\text{min}^{-1}$/μU/mL*,†	
Suh et al. (2011)[33]	15 Boys, 15 girls (13.1 yr)	Diet only	27.1	2 day/wk diet education program	12 wk	318.8 μU/mL in insulin AUC	OGTT
		AE+diet	26.3	3 day/wk, 40 min/day, 60%–70% of VO_{2max}+2 day /wk diet education program		–3,007.9 μU/mL in insulin AUC	
		RE+diet	25.3	3 day/wk, 60 min/day, 60% of 1 RM, 2–3 sets, 10–12 reps+2 day/wk diet education program		–1,646.4 μU/mL in insulin AUC	
Resistance+aerobic exercise							
Ackel-D'Elia et al. (2014)[37]	22 Boys, 50 girls (15–19 yr)	LPA	34.6	3 day/wk, 60 min/day, recreational team sports, gymnastics, walking	6 mon	–0.3	HOMA-IR
		AE	35.1	3 day/wk, 60 min/day, treadmill		–0.3	
		AE+RE	35.1	3 day/wk, 60 min/day, 30 min AE+30 min RE, 10 exercises, 3 sets, 6–20 reps		–0.8	
Bharath et al. (2018)[38]	40 Girls (mean ± SD, 14.7 ± 1 yr)	Control	30.0	No treatment	12 wk	0.1	HOMA-IR
		AE+RE	30.0	3 day/wk, 60 min/day, 30 min AE, 40%–70% of HRR+20 min RE, 10 band exercises, 15–20 reps		–4.8	
Dâmaso et al. (2014)[39]	139 (15–19 yr)	AE	35.7	3 day/wk, 60 min/day, 50%–70% of VO_{2peak}	1 yr	–0.2†	QUICKI
		AE+RE	36.7	3 day/wk, 60 min/day, 30 min AE+30 min RE, 6–20 RM, 3 sets		–0.2†	
Davis et al. (2009)[40]	41 Girls (mean ± SD, 15.2 ± 1.1 yr)	Control	34.6	No treatment	16 wk	$-0.03\times10^{-4}\text{min}^{-1}$/μU/mL	FSIVGTT
		NE	33.8	1 day/wk nutrition education (90 min)		$0.3\times10^{-4}\text{min}^{-1}$/μU/mL	
		NE+RE	32.8	2 day/wk, 60 min/day, 10 whole-body RE		$-0.4\times10^{-4}\text{min}^{-1}$/μU/mL	
		NE+AE+RE	33.6	2 day/wk, 60 min/day, 30 min AE+30 min RE		$0.1\times10^{-4}\text{min}^{-1}$/μU/mL	

(*Continued to the next page*)

Table 2. Continued

Author (year)	Subject	Treatment	Average BMI (kg/m²)	Exercise prescription	Duration	ΔInsulin resistance	Measure
Davis et al. (2011)[41]	38 Girls (14–18 yr)	Control	36.4	No treatment	16 wk	–4.0%†	HOMA-IR
		AE+RE	32.4	2 day/wk, 60–90 min/day, 30–45 min AE (70%–85% of HR_{max})+30–45 min RE, 2 sets, 8–12 reps		–21.0%*,†	
		AE+RE+MI	34.6	2 day/wk, 60–90 min/day, 4 individual and 4 group sessions		NA	
de Piano et al. (2012)[42]	27 Boys, 31 girls (15–19 yr)	AE (no NAFLD)	33.5	3 day/wk, 60 min/day, 50%–70% of VO_{2peak}	12 mon	–0.1	HOMA-IR
		AE (with NAFLD)	38.0	3 day/wk, 60 min/day, 50%–70% of VO_{2peak}		–1.6	
		AE+RE (no NAFLD)	36.5	3 day/wk, 60 min/day, 30 min AE+30 min RE, 3 sets, 6–20 reps		–1.4*	
		AE+RE (with NAFLD)	38.4	3 day/wk, 60 min/day, 30 min AE+30 min RE, 3 sets, 6–20 reps		–2.1*	
Farpour-Lambert et al. (2009)[43]	16 Boys, 28 girls (6–11 yr)	Control	25.1	No treatment	3 mon	0.62†	HOMA-IR
		AE+RE	25.4	3 day/wk, 60 min/day, 30 min AE, 55%–65% of VO_{2max}+20 min RE+10 min stretching		0.99†	
Foschini et al. (2010)[44]	15 Boys, 17 girls (mean ± SD, 16.5 ± 1.7 yr)	AE+RE (LP)	36.5	3 day/wk, 60 min/day, 30 min AE+30 min RE, 6–20 RM, 3 sets	14 wk	–0.3	HOMA-IR
		AE+RE (DUP)	37.7	3 day/wk, 60 min/day, 30 min AE+30 min RE, 3 sets (day 1: 15–20 RM, day 2: 10–12 RM, day 3: 6–8 RM)		–1.2†	
Inoue et al. (2015)[45]	17 Boys, 28 girls (15–18 yr)	AE	35.1	3 day/wk, 60 min/day, 1–13 wk: AE only, 14–26 wk: 30 min AE+30 min RE, > 75% of 1 RM, 3 sets	1 yr	–8.2%	HOMA-IR
		AE+RE (LP)	36.4	3 day/wk, 60 min/day, 30 min AE+30 min RE, 6–20 RM, 3 sets		–48.9%*,†	
		AE+RE (DUP)	38.2	3 day/wk, 60 min/day, 30 min AE+30 min RE, 3 sets (day 1: 15–20 RM, day 2: 10–12 RM, day 3: 6–8 RM)		–46.2%*,†	
Lee et al. (2019)[46]	42 Boys, 76 girls (12–17 yr)	AE	33.7	3 day/wk, 60 min/day, 50%–65% of VO_{2peak}	6 mon	1.7 mg/kg/min†,‡	Euglycemic clamp
		RE	33.4	3 day/wk, 60 min/day, 8 exercises, 2 sets, 12–15 reps		0.7 mg/kg/min†	
		AE+RE	32.3	3 day/wk, 60 min/day (30 min AE+30 min RE)		1.2 mg/kg/min†	

*Significantly different from the control or other groups (vs. RE or AE+RE), $P<0.05$; †Significantly different from baseline within group, $P<0.05$; ‡Significantly different from RE, $P<0.05$.

BMI, body mass index; Δ, change score; RE, resistance exercise, reps, repetitions; HOMA-IR, homeostatic model assessment for insulin resistance; NE, nutrition education; FSIVGTT, frequently sampled intravenous glucose tolerance test; AA, African-American; SD, standard deviation; AE, aerobic exercise; VO_{2peak}, peak oxygen uptake; 1-RM, 1-repetition maximum; VO_{2max}, maximum oxygen consumption; OGTT, oral glucose tolerance test; LPA, leisure physical activity; HRR, heart rate reserve; HR_{max}, heart rate max; MI, motivational interview; NA, not available; NAFLD, nonalcoholic fatty liver disease; LP, linear periodization; DUP, daily undulating periodization.

the eight studies demonstrated significant improvements in insulin sensitivity following resistance exercise alone[24,26] or combined with caloric restriction.[33] Following 16 weeks of resistance exercise, Shaibi et al.[24] demonstrated significant improvements in insulin sensitivity (45%), as measured by frequently sampled intravenous glucose tolerance tests, compared with non-exercising controls (–0.9%) in overweight Latino adolescent boys, and the changes in insulin sensitivity were independent of changes in total fat and lean body mass. Lee and colleagues also examined the effects of 3 months of resistance exercise versus aerobic exercise (without caloric restriction) on insulin sensitivity, as measured by a 3-hour hyperinsulinemic-euglycemic clamp technique, in previously sedentary adolescent boys[26] and girls[32] with obesity. Although resistance exercise produced a significant improvement in insulin sensitivity (28%) in adolescent boys, this was not the case in girls. Compared with the non-exercising controls, significant improvements in insulin sensitivity (33%) were observed only following aerobic exercise in girls. These findings suggest the presence of sex differences in insulin sensitivity changes associated with resistance exercise training in adolescents.

Currently, the effects of resistance exercise on oral glucose tolerance are not fully established, with only five randomized controlled trials completed to date.[26,30,32-34] Only one of those studies[33] demonstrated any significant improvements in 2-hour and insulin levels or glucose and insulin areas under the curve (AUCs) following 12–16 weeks of resistance exercise training with or without dietary modification. Suh et al.[33] found that despite significant increases in body weight and visceral fat following a 12-week resistance exercise program with caloric restriction, insulin AUC was reduced from the baseline values; however those reductions did not differ significantly from the diet-only group in a mixed group of overweight Korean boys and girls.

EFFECTS OF RESISTANCE EXERCISE ON TRADITIONAL CVD RISK FACTORS

It is well known that obesity, particularly abdominal obesity, is associated with high blood pressure and dyslipidemia in children and adolescents, independent of BMI.[10,11,55,56] Furthermore, adolescents with obesity have greater arterial stiffness and endothelial dysfunction than their lean counterparts.[57-60] Aortic pulse wave velocity (aPWV), a measure of arterial stiffness, and carotid artery intima-media thickness (cIMT) have been suggested as markers of subclinical atherosclerosis and have been used as surrogate measures of cardiovascular events in adults.[61] Iannuzzi et al.[60] showed that both boys and girls with obesity (6–14 years) have significantly higher systolic and diastolic blood pressure and increased cIMT and arterial stiffness than their lean controls. Gungor et al.[59] reported that aPWV is significantly increased in adolescents with obesity compared with their normal-weight peers. Increased cIMT and arterial stiffness in youth with obesity could increase their risk of atherosclerotic CVD if left untreated.[59,60]

The effects of resistance exercise (alone or combined with a low caloric diet) on blood pressure and lipid profiles have been examined in children and adolescents with obesity (Table 3).[31,35,36,62] Sung et al.[36] reported no reductions in total or low-density lipoprotein (LDL) cholesterol following 6 weeks of resistance exercise combined with a low caloric diet (900–1,200 kcal/day, 20%–25% fat) compared with the low caloric diet only group in Chinese children with obesity (8–11 years, > 120% of the median weight for height). The previously mentioned 3-month intervention studies by Lee's group[62] also found no significant changes in aPWV, cIMT, blood pressure, or lipid profiles following either resistance or aerobic exercise alone (e.g., no caloric restriction) despite significant reductions in body fat. Perhaps, the lack of improvements in traditional CVD markers could be due to a basement effect because the study participants had normal blood pressure and lipid values prior to the exercise intervention. Alternatively, these results could indicate that greater obesity reduction is required to improve CVD markers in youth with obesity. However, a recent meta-analysis of randomized controlled trials in adults[63] reported that aerobic exercise, but not resistance exercise, was associated with significant improvements in arterial stiffness. Nevertheless, given the small number of randomized controlled trials and the relatively short resistance exercise interventions (8–16 weeks), the effects of resistance exercise alone on CVD markers are inconclusive in youth with obesity. Further studies with longer-term interventions are needed to verify the independent role of resistance exercise in improving traditional and non-traditional CVD markers in youth.

EFFECTS OF RESISTANCE EXERCISE COMBINED WITH AEROBIC EXERCISE ON CARDIOMETABOLIC MARKERS

In children and adolescents, several studies have examined whether combined exercise is better than aerobic exercise alone for improving total and abdominal fat (Table 1), insulin resistance (Table 2), and traditional CVD risk factors (Table 3). For example, Dâmaso et al.[39] examined the effects of 12 months of combined aerobic and resistance exercise (3 times/wk, 60 minutes per session, 30 minutes of aerobic exercise at 50%–70% of VO_{2peak}, and 30 minutes of resistance exercise at 6–20 RM/3 sets) versus aerobic exercise alone (3 times/wk, 50 minutes per session, 50%–70% of VO_{2peak}) on total and abdominal fat and homeostatic model assessment for insulin resistance (HOMA-IR) in 139 adolescents with obesity (age 15–19 years). Although there were no significant differences in weight loss (–12.3 kg vs. –8.8 kg) or HOMA-IR (–1.2 vs. –0.9), reductions in total fat (–14.2 kg vs. –8.1 kg), visceral fat (–1.6 cm^2 vs. –1.4 cm^2), abdominal subcutaneous fat (–0.9 cm^2 vs. –0.5 cm^2) and LDL cholesterol (–12.1 mg/dL vs. –4.8 mg/dL) were all signifi-

Table 3. Effects of resistance exercise alone or combined with aerobic exercise on traditional cardiovascular disease markers

Author (year)	Subject	Treatment	Average BMI (kg/m^2)	Exercise prescription	Duration	Δ SBP (mmHg)	Δ DBP (mmHg)	Δ TG	ΔTC	ΔHDL	ΔLDL
Resistance exercise											
Benson et al. (2008)[31]	46 Boys, 32 girls (10–15 yr)	Control	21.9	No treatment	8 wk				–0.11 mmol/L	–0.1 mmol/L	–0.1 mmol/L
		RE	23.2	2 day/wk, 11 exercises, 80% of peak strength, 2 sets, 8 reps					0.04 mmol/L	0.1 mmol/L	–0.1 mmol/L
Horner et al. (2015)[62]	41 Boys, 40 girls (12–18 yr)	Control	34.2	No treatment	12 wk	1.1	0.1	–4.7 mg/dL	–2.3 mg/dL	–0.9 mg/dL	–1.4 mg/dL
		AE	34.4	3 day/wk, 60 min/day, 60%–75% VO_{2peak} (treadmill, elliptical)		–3.4	–3.0	–23.8 mg/dL	–5.0 mg/dL	–4.8 mg/dL	–5.1 mg/dL
		RE	35.7	3 day/wk, 60 min/day, 10 exercises, 2 sets, 8–12 reps to fatigue		3.3	3.3	–15.3 mg/dL	–16.1 mg/dL	–0.3 mg/dL	–12.5 mg/dL
Kelly et al. (2015)[35]	26 Boys (14–18 yr)	Control	34.2	No treatment	16 wk	–5.1	0.8				
		RE	33.1	3 day/wk, 60 min/day, 1–4 wk: 1 set 12 reps, 5–10 wk: 2–3 sets, 12 reps, 11–16 wk: 3–4 sets, 12 reps		–3.8	1.0				
Sung et al. (2002)[36]	54 Boys, 28 girls (8–10 yr)	Control	24.6	Low energy diet (900–1,200 kcal) 75 min/session	6 wk			0.1 mmol/L	–0.3 mmol/L*	–0.1 mmol/L*	–0.2 mmol/L
		RE	25.5	20 Workout stations, 75%–100% of 10 RM				0.3 mmol/L	–0.3 mmol/L*	–0.1 mmol/L	–0.4 mmol/L*
Resistance+aerobic exercise											
Bharath et al. (2018)[38]	40 Girls (mean±SD, 14.7±1 yr)	Control	30.0	No treatment	12 wk	2.0	0.0				
		AE+RE	30.0	3 day/wk, 60 min/day, 30 min AE, 40%–70% of HRR+20 min RE, 10 band exercises, 15–20 reps		–1.0	–2.0				
Dâmaso et al. (2014)[39]	139 (15–19 yr)	AE	35.7	3 day/wk, 60 min/day, 50%–70% of VO_{2peak}	1 yr			–27.2 mg/dL*	–6.8 mg/dL*	1.0 mg/dL	–4.8 mg/dL
		AE+RE	36.7	3 day/wk, 60 min/day, 30 min AE+30 min RE, 6–20 RM, 3 sets				–19.0 mg/dL*	–13.5 mg/dL*	2.4 mg/dL*	–12.1 mg/dL*,†
de Piano et al. (2012)[42]	27 Boys, 31 girls (15–19 yr)	AE (no NAFLD)	33.5	3 day/wk, 60 min/day, 50%–70% of VO_{2peak}	12 mon			–31.1 mg/dL	–3.5 mg/dL	0.1 mg/dL	2.8 mg/dL
		AE (with NAFLD)	38.0	3 day/wk, 60 min/day, 50%–70% of VO_{2peak}				–14.8 mg/dL	3.6 mg/dL	2.9 mg/dL	3.6 mg/dL
		AE+RE (no NAFLD)	36.5	3 day/wk, 60 min/day, 30 min AE+30 min RE, 3 sets, 6–20 reps				–6.3 mg/dL	–17.4 mg/dL*	0.9 mg/dL	–17.1 mg/dL*,†
		AE+RE (with NAFLD)	38.4	3 day/wk, 60 min/day, 30 min AE+30 min RE, 3 sets, 6–20 reps				–8.3 mg/dL	–17.1 mg/dL*,†	–0.2 mg/dL	–15.3 mg/dL*,†
Farpour-Lambert et al. (2009)[43]	16 Boys, 28 girls (6–11 yr)	Control	25.1	No treatment	3 mon	4.4*	4.7*	0.12 mmol/L	–0.14 mg/dL	–0.03 mg/dL	–0.17 mg/dL
		AE+RE	25.4	3 day/wk, 60 min/day, 30 min AE, 55%–65% of VO_{2max}+20 min RE+10 min stretching		–1.9*	–1.3	0.04 mmol/L	–0.22 mg/dL*	–0.06 mg/dL	–0.18 mg/dL

(*Continued to the next page*)

Table 3. Continued

Author (year)	Subject	Treatment	Average BMI (kg/m²)	Exercise prescription	Duration	Δ SBP (mmHg)	Δ DBP (mmHg)	Δ TG	ΔTC	ΔHDL	ΔLDL
Foschini et al. (2010)[44]	15 Boys, 17 girls (mean ± SD, 16.5 ± 1.7 yr)	AE+RE (LP)	36.5	3 day/wk, 60 min/day, 30 min AE+30 min RE, 6–20 RM, 3 sets	14 wk	–18.6*	–9.6*	NR	–17.0 mg/dL*	0.5 mg/dL	–14.2 mg/dL*
		AE+RE (DUP)	37.7	3 day/wk, 60 min/day, 30 min AE+30 min RE, 3 sets (day 1: 15–20 RM, day 2: 10–12 RM, day 3: 6–8 RM)		–18.4*,†	–11.3*		–23.4 mg/dL*	1.7 mg/dL	–22.9 mg/dL*
Inoue et al. (2015)[45]	17 Boys, 28 girls (15–18 yr)	AE	35.1	3 day/wk, 60 min/day, 1–13 wk: AE only, 14–26 wk: 30 min AE+30 min RE, >75% of 1 RM, 3 sets	1 yr			–28.7 mg/dL*	2.6 mg/dL	NR	2.1 mg/dL
		AE+RE (LP)	36.4	3 day/wk, 60 min/day, 30 min AE+30 min RE, 6–20 RM, 3 sets				–4.8 mg/dL	–14.6 mg/dL*	NR	–13.4 mg/dL*,†
		AE+RE (DUP)	38.2	3 day/wk, 60 min/day, 30 min AE+30 min RE, 3 sets (day 1: 15–20 RM, day 2: 10–12 RM, day 3: 6–8 RM)				–7.5 mg/dL	–18.1 mg/dL*,†	NR	–17.2 mg/dL*,†
Monteiro et al. (2015)[47]	27 Boys, 21 girls (11–17 yr)	Control	31.0	No treatment	20 wk			19.4 mg/dL*	–20.4 mg/dL*	–6.6 mg/dL*	–10.4 mg/dL*
		AE	30.2	3 day/wk, 50 min/day, 65%–85% of VO_{2peak}				–31.9 mg/dL*	–29.6 mg/dL*	3.0 mg/dL†	–26.0 mg/dL*
		AE+RE	33.2	3 day/wk, 60 min/day, 30 min AE+30 min RE, 55%–75% of 1 RM, 1–2 sets, 12–20 reps				–26.3 mg/dL*	–40.2 mg/dL*	–5.5 mg/dL*	–33.9 mg/dL*
Park et al. (2012)[64]	14 Boys, 15 girls (12–13 yr)	Control	24.3	No treatment	12 wk	1.0	0	0.3 mmol/L	0.5 mmol/L	0.2 mmol/L	0.2 mmol/L
		AE+RE	24.4	3 day/wk, 80 min/day, 30 min AE, 60%–70% HRR, treadmill+RE, 7 exercises, 2 sets, 8–12 reps to fatigue		3.0	1.0	0.1 mmol/L	0.2 mmol/L	0.3 mmol/L	0.1 mmol/L
Sigal et al. (2014)[48] & Alberga et al. (2015)[49]	91 Boys, 213 girls (14–18 yr)	Control	34.1	Daily energy deficit <250 kcal,	26 wk	–4.0*	–1.0				
		AE	34.7	4 day/wk, 20–40 min/day, 65%–85% of HR_{max}		–5.0*	–3.0*				
		RE	35.1	4 day/wk, 20–40 min/day, whole–body exercises, 2–3 sets, 6–15 reps		–4.0*	–2.0*				
		AE+RE	34.6	4 day/wk, 20–40 min, AE+RE		–1.0	–2.0				
Woo et al. (2004)[50]	54 Boys, 28 girls (9–12 yr)	Diet only	24.5	Low energy diet (900–1,200 kcal)	6 wk			0.0 mmol/L	–0.3 mmol/L*	–0.1 mmol/L*	–0.2 mmol/L
		Diet+AE+RE	25.4	Low energy diet+2 day/wk, 75 min/day, AE, 18 workout stations, 60%–70% of HR_{max}+30 min RE				0.3 mmol/L	–0.3 mmol/L*	–0.1 mmol/L*	–0.3 mmol/L*
		After 6 wk									
		Diet only	24.7	Low energy diet (900–1,200 kcal)	1 yr			0.2 mmol/L	–0.2 mmol/L*	0.2 mmol/L	–0.4 mmol/L*
		Detraining	26.1	2-Monthly diet monitoring program				0.1 mmol/L	–0.1 mmol/L	0.0 mmol/L	–0.2 mmol/L
		Continued training	25.3	Weekly exercise program				0.1 mmol/L	0.0 mmol/L	0.2 mmol/L*	–0.3 mmol/L*

*Significantly different from baseline within group, $P<0.05$; †Significantly different from the control or other groups (vs. RE or AE+RE), $P<0.05$.
BMI, body mass index; Δ, change score; SBP, systolic blood pressure; DBP, diastolic blood pressure; TG, triglyceride; TC, total cholesterol; HDL, high density lipoprotein; LDL, low density lipoprotein; RE, resistance exercise; reps, repetitions; AE, aerobic exercise; VO_{2peak}, peak oxygen uptake; 1-RM, 1-repetition maximum; SD, standard deviation; HRR, heart rate reserve; NAFLD, nonalcoholic fatty liver disease; VO_{2max}, maximum oxygen consumption; LP, linear periodization; DUP, daily undulating periodization; HR_{max}, heart rate max.

cantly greater in the combined exercise group than in the aerobic exercise only group. The same research group[37] also examined the effects of 6 months of leisure-time physical activity, aerobic exercise alone, and combined aerobic and resistance exercise on body composition and insulin resistance in adolescents with obesity (age 15–19 years). When the exercise time was matched between groups (3 times/wk, 60 minutes per session for 6 months), the reductions in body weight, BMI, and total fat mass and increases in FFM were significantly greater in the combined exercise group than in the aerobic exercise only group.

To the best of our knowledge, only two randomized trials[46,48] have examined the effects of all three exercise modalities (aerobic, resistance, and combined exercise) together in a pediatric population. Sigal et al.[48] investigated the influence of aerobic alone, resistance alone, and combined aerobic and resistance exercise training with caloric restriction (energy deficit 250 kcal/day for all groups) on total body fat (%) and cardiometabolic risk factors in a large sample of adolescents with obesity (n = 304, age 14–18 years). In that study[48,49], all exercise groups had reduced total body fat (aerobic, –1.2 kg; resistance, –1.3 kg; combined, –1.7 kg) of a similar magnitude, as measured by the whole-body MRI technique. Abdominal subcutaneous fat also decreased similarly in all exercise groups (aerobic, –16.2 cm^2; resistance, –22.7 cm^2; combined exercise, –18.7 cm^2) compared with controls (5.6 cm^2); however, no significant group differences were observed in the changes in visceral fat, fasting insulin, fasting glucose or 2-hour glucose, or lipid profiles.[48,49]

Recently, Lee et al.[46] examined whether combined aerobic and resistance exercise is more effective than either aerobic or resistance exercise alone (without caloric restriction) in improving insulin sensitivity and reducing ectopic fat in the liver and skeletal muscle lipids in adolescents with overweight or obesity (n = 118, age 12–17 years). In that study[46], exercise duration was similar among groups (all groups performed 3 day/week, 60 minutes/session for 6 months), and the exercise compliance did not differ between groups (aerobic, 91%; resistance, 89%; and combined exercise, 89%). Although all three types of exercise reduced body fat (%) and improved insulin sensitivity and oral glucose tolerance test 2-hour glucose, combined aerobic and resistance exercise and aerobic exercise alone were similarly beneficial in improving insulin sensitivity, and aerobic exercise alone was more effective than resistance exercise alone in improving insulin sensitivity.

CONCLUSION

Evidence demonstrates a strong association between muscular strength and cardiometabolic abnormalities in children and adolescents with obesity. Accordingly, current public physical activity guidelines[22] recommend that children and adolescents engage in muscle strengthening physical activities at least 3 days a week, in addition to aerobic activity.

To date, only a few randomized trials have examined the effects of resistance exercise alone on total and abdominal obesity and cardiometabolic risk markers in children and adolescents with obesity. The pediatric literature contains wide variations in study design, resistance intervention duration (6 weeks–12 months) and frequency, subject characteristics (e.g., studying one or both sexes, pubertal status) and adherence to the prescribed exercise regimens. Limited evidence from well-designed randomized trials[46,48] suggests that in the absence of weight loss, resistance exercise alone is associated with a significant increase in muscular strength and reductions in total fat and insulin resistance in previously sedentary adolescents with obesity. However, whether resistance training alone is associated with improvements in CVD factors is less clear. Nevertheless, incorporating resistance exercise into weight management interventions could be a useful strategy for improving muscular fitness and reducing obesity-related health risks in children and adolescents.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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