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ACADEMIC LITERATURE REVIEW

Resistance training induced increase in VO_2max in young and older subjects

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Abstract It is an undeniable fact that resistance training (RT) is a potent stimulus for muscle hypertrophy and strength gain, but it is less understood whether RT can increase maximal aerobic capacity (VO_2max). The purpose of this brief review is to discuss whether or not RT enhances VO_2max in young (20–40 years) and older subjects (>60 years). Only 3 of 17 studies involving young subjects have indicated significant increases in VO_2max following RT, while six of nine studies in older subjects have reported significant improvements in VO_2max following RT. There was a significant negative correlation between the initial VO_2max and RT-induced change in VO_2max. This result suggests that RT-induced increase in VO_2max is dependent upon the subject's initial VO_2max. The RT-induced increase in VO_2max may be elicited when their initial relative VO_2max is lower than 25 ml/kg/min for older subjects and lower than 40 ml/kg/min for young subjects. Thus, RT can be expected to improve concurrently both muscular and cardiovascular fitnesses within a single mode of RT when young and old persons have initially low fitness levels.

Keywords Strength training · Aerobic training · Muscle hypertrophy · Cardiovascular fitness

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Introduction

Age-related sarcopenia characterized by reductions in skeletal muscle mass and function is associated with an increased risk of disability, impaired gait, falls, and osteoporosis [6, 51, 54]. Furthermore, it increases the risk of developing a wide range of chronic disorders, including atherosclerosis [3, 38], insulin resistance, and hyperglycemia [31, 42]. Although the prevalence of sarcopenia is highly dependent upon the applied diagnostic criteria [8], about 10 % of the older population has a severe degree of sarcopenia, and about 30 % has a more moderate degree of sarcopenia [29]. In addition, the age-related decrease in maximal oxygen uptake (VO_2max) is associated with an increased risk of cardiovascular disease [48], and there is a strong correlation between skeletal muscle mass and VO_2max [43]. It is well known, therefore, that maintaining optimal levels of skeletal muscle mass as well as VO_2max is important to the health of older populations.

Adaptations to aerobic and resistance exercise training are highly specific, and several societies [5, 19] have published separate aerobic and resistance training guidelines to optimize muscle hypertrophy and strength gains as well as to improve VO_2max. In general, the magnitude of the acquired training adaptation is proportional to the training stimulus and is also dependent on the individual's training experience and/or initial physical fitness level. The guidelines [5, 19] propose a training frequency of ≥5 days per week of moderate or ≥3 days per week of vigorous aerobic training or a combination of moderate and vigorous aerobic training on ≥3–5 days per week and 2–3 days per week of resistance training. Because the typical duration of these training sessions is approximately 60 min, including warm-up and cool-down, about 300–480 min (5–8 h) per week would be needed to complete the program. However, the vigorous training intensities and the high frequencies suggested might constitute a major barrier for older populations, discouraging them from participating in the training programs. Additionally, performing resistance and aerobic exercise training concurrently within the same day or a couple of days inhibits the developments of strength and muscle hypertrophy compared with resistance training alone [14]. Thus, it would be advantageous to concurrently improve both cardiovascular (VO_2max) and muscular (muscle hypertrophy and functional ability) fitnesses within a single mode of exercise training. Resistance training (RT) is a potent stimulus for muscle hypertrophy, but it is less understood whether RT can increase VO_2max. It is largely unknown whether there are differences in cardiorespiratory responses to RT between young and old men and women. In addition, it is well known that absolute and relative VO_2max are lower in older adults than in young adults [23], and initial VO_2max is inversely correlated with the absolute improvement in VO_2max [30]. Therefore, the purpose of this brief review is to discuss whether or not resistance training enhances VO_2max as well as muscle size and strength in young (20–40 years) and older subjects (>60 years).

Methods

Literature search

An online search using MEDLINE was performed to obtain articles that examined the effects of resistance training on maximum oxygen uptake, utilizing the following keywords: "resistance training," "strength training," "maximum oxygen uptake," "VO_2max," "cardiovascular adaptations," "concurrent resistance and endurance training," "concurrent strength and endurance training," "combined strength and endurance training," and "combined strength and aerobic training." References from pertinent articles and names of the authors cited were cross-referenced to locate any further relevant articles not found with the initial search.

Inclusion criteria

In order to investigate the effects of traditional resistance training on VO_2max as well as muscle size and strength, we included only studies that used traditional high-intensity resistance training programs. Therefore, circuit training was excluded because the goal of circuit training is to improve aerobic capacity. Studies were also excluded if resistance training was combined with other factors such as vibration and blood flow restriction to an exercised muscle. Furthermore, to be included, a study also needed to meet the following criteria: (a) study population in which subjects could be healthy and sedentary, untrained or physically active, but not participating in regular strength and endurance training. The mean age of subjects is between the ages 20 to 40 for young age and more than 60 years for older age groups; (b) training intensity and duration in which the study had to include training intensities >50 % of one repetition maximum (1RM) [19], and in order to allow a sufficient period for physiologic adaptation, the duration of the study had to be >6 weeks [1]; (c) outcome measure, wherein the study needed to investigate VO_2max or VO_2peak measured on a treadmill or cycle ergometer in addition to muscle strength, muscle size, and/or fat-free mass; and (d) language in which the search was limited to original research that was written in English.

Physiological factors for improving VO_2max

The American College of Sports Medicine recommends performing 20–60 min of aerobic exercise (e.g., walking, running, and cycling) at an exercise intensity of 40–50 % VO_2max or higher, 3–5 days per week to increase VO_2max [19]. Generally, the effects of aerobic training increase in a dose-dependent manner with exercise intensity, and it is known that training at an exercise intensity of 90–100 % VO_2max is the most effective way to increase VO_2max [52]. According to the Fick principle, the improvement in both cardiac outputs (stroke volume and heart rate) and arterial-venous oxygen difference (a-vO_2 diff) contribute to increases in VO_2max. Evidence from aerobic exercise training suggests that the increase in maximal stroke volume (SVmax) is likely due to the volume overload-induced left ventricular hypertrophy [16]. In addition, enhanced sensitivity to catecholamines and an increase in blood volume may also contribute to the increase in SVmax [46]. The increment in a-vO_2 diff is mainly induced by an increase in capillary density and myoglobin concentration of muscle with quantitative and qualitative alterations of mitochondria in muscle [12, 22, 27].

Effects of resistance training on VO_2max

Young subjects

RT markedly increases muscle strength (10–97 %) [7, 10, 12, 13, 15, 20, 25, 28, 32, 34–36, 41, 44, 45, 47], but most studies have shown that RT does not significantly increase VO_2max. Only 3 of 17 studies [7, 10, 11, 13, 15, 20, 25, 26, 28, 32, 34–37, 41, 44, 45, 47] involving young subjects have indicated significant increases in VO_2max following RT (Table 1).

Effects of training intensity

Various exercise intensities, ranging from 3RM to 28RM (about 50 to 90 % of 1RM), were used in the previous studies that measured the effects of RT on VO_2max for young subjects. To illustrate, 12 weeks of RT at 15RM

Table 1 Summary of resistance training studies in young subjects

Author	Sex	Age	Subject	Group	Period frequency	Training program	Muscle strength			Muscle size		VO$_2$max (ml/kg/min)			
						Equipment		%	%/S		%	Mode	Baseline	%	%/S
Hickson et al. [26]	M	23	Healthy active	RT	10 weeks	80 % 1RM 5 reps	KE	50	1.00	–	–	T	47.8	NS (2)	0.04
					5 days/week	3 sets (F and M)	1RM								
Hickson [25]	M	22	Physically active	RT	10 weeks	80 % 1RM 5 reps	SQ	44	0.88	–	–	T	46.7	NS (1)	0.03
	F				5 days/week	3–5 sets (F and M)	1RM								
Stone et al. [47]	M	College Age	Healthy sedentary	RT	8 weeks 6 days/week	5–10RM 3–5 sets (F and M)	–	–	–	LBM	4	E	39.5	6	0.13
Rutherford et al. [41]	M	28	Physically active	KE	12 weeks	80 % 1RM 6 reps	KE	20	0.56	–	–	E	2.91[a]	NS (−2)	−0.06
					3 days/week	4 sets (M)	IsoM								
Nelson et al. [37]	M	27	Healthy untrained	RT	20 weeks 4 days/week	6 maximal-effort reps, 3 sets Cybex II	KE IsoK	45	0.56	fCSA	15	T	55.3	NS (1)	0.01
Craig et al. [13]	M	23.5	University student	RT	10 weeks	75 % 1RM 8–10 reps	LP	6	0.20	LBM	4	T	46.1	NS (1)	0.03
					3 days/week	3 sets (M)	1RM								
Marcinik et al. [34]	M	29	Healthy untrained	RT	12 weeks 3 days/week	8–20RM 3 sets (M)	KE 1RM	30	0.83	–	–	T	44.7	NS (0)	0.01
McCarthy et al. [35]	M	27.9	Untrained	RT	10 weeks 3 days/week	6RM 3 sets (F and M)	KE IsoM	12	0.40	FFM	3	E	39.3	9	0.31
Dolezal et al. [15]	M	20.1	Physically active	RT	10 weeks 3 days/week	4–12RM 3 sets (F and M)	SQ 1RM	23	0.77	FFM	4	T	50.4	NS (0)	0.01
Bell et al. [7]	M	22.3	Physically active	RT	12 weeks	72–84 % 1RM 4–12 reps	KE	32	0.89	fCSA, I	27	E	4.35[a]	NS (−1)	−0.04
					3 days/week	2–6 sets (F and M)	1RM			fCSA, II	28				
	F							58	1.61				2.84[a]	NS (−6)	−0.17
Campos et al. [10]	M	21.1	Healthy untrained	Low Rep	8 weeks 2–3 days/week	3–5RM 4 sets (NR)	LP 1RM	61	3.00	fCSA IIa	23	E	50.3	NS (−4)	−0.18
		20.7		Int Rep		9–11RM 3 sets (NR)		36	1.80		16		48.1	NS (−5)	−0.25
		20.4		High Rep		20–28RM 2 sets (NR)		32	1.60		NS (8)		51.0	NS (3)	0.15
Glowacki et al. [20]	M	23	Untrained	RT	12 weeks	75–85 % 1RM 6–10 reps	KE	10	0.33	LBM	4	T	44.9	NS (0)	0.01
					2–3 days/week	3 sets (F and M)	IsoK								
Loveless et al. [32]	M	25	Healthy untrained	SQ	8 weeks	85 % 1RM 5 reps	SQ	97	4.04	LLM	5	E	46.7	NS (0)	0.00

Table 1 (continued)

Author	Sex	Age	Subject	Group	Period frequency	Training program	Muscle strength			Muscle size		VO_2max (ml/kg/min)			
						Equipment		%	%/S		%	Mode	Baseline	%	%/S
Minahan et al. [36]	M	23	Healthy untrained	SQ	3 days/week 8 weeks	4 sets (M) 85 % 1RM 5 reps	1RM SQ	90	3.75	–	–	E	46.9	NS (−1)	−0.05
Shaw et al. [45]	M	25	Healthy sedentary	RT	3 days/week 16 weeks	4 sets (M) 60 % 1RM 15 reps	1RM LP	65	1.35	–	–	E	35.7	13	0.27
Hu et al. [28]	M	32.2	Physically inactive	RT	3 days/week 10 weeks 2–3 days/week	3 sets (F and M) 40–90 % 1RM (F and M)	1RM SQ 1RM	28	1.22	LBM	1	E	35.9	NS (8)	0.34
Cesar Mde et al. [11]	F	21	Healthy untrained	RT	12 weeks 3 days/week	15RM 3 sets (M)	KE 1RM	27	0.75	–	–	T	2.02[a]	NS (5)	0.12

M male, *F* female, *RT* whole body resistance training, *KE* knee extension, *Low Rep* low repetition resistance training, *Int Rep* intermediate repetition resistance training, *High Rep* high repetition resistance training, *SQ* squat, *1RM* one repetition maximum, *IsoM* isometric, *IsoK* isokinetic, *LP* leg press, *LBM* lean body mass, *FFM* fat-free mass, *fCSA* fiber cross-sectional area, *LLM* lean leg mass, *NS* not significant, *T* treadmill, *E* ergometer, *%/S* percent change per session, *F and M* free weight and machine, *M* machine, *NR* not reported

[a] Reported only in absolute value (in liter per minute)

(about 65 % of 1RM, 3 days per week, total 36 sessions) increased knee extension 1RM strength 27 % (0.75 % per session), while 10 weeks of RT at 5RM (85 % of 1RM, 5 days per week, total 50 sessions) increased knee extension 1RM strength 50 % (1.0 % per session) but neither significantly increased VO_2max [11, 26]. Furthermore, Campos et al. [10] divided subjects into three groups: a 3–5RM group, a 9–11RM group, and a 20–28RM group and measured VO_2max for young subjects after 10 weeks of RT. The study found that VO_2max did not change regardless of exercise intensity, while 1RM and muscle endurance increased following training in all groups. The other studies performed 8–12 weeks of whole body RT at various exercise intensities and found no benefit of RT to improve VO_2max. The results of these studies suggest that there is no significant relationship between a change in VO_2max and training intensity in young adults (Table 1).

Effects of training volume

Total training volume differs between whole body exercise (five to eight exercises) and a single exercise. In 3 of 15 studies [32, 36, 41], subjects performed multiple sets of a single exercise in the lower body such as squat or knee extension. In these studies, 1RM strength markedly improved after 8–12 weeks of RT, but VO_2max did not significantly change. Other studies performed multiple sets of whole body RT at exercise intensities of about 5–10RM (Table 1). Compared to the single exercise, whole body RT increased the total amount of skeletal muscle mass (e.g., increase in fat-free mass), which is thought to be related, in part, to changes in VO_2max [17]. However, despite the increases in fat-free mass or muscle fiber size, these studies still observed no significant increase in VO_2max [7, 15, 20]. Furthermore, it is reported that there was no significant change in mitochondria enzyme activity (e.g., citrate synthase and succinate dehydrogenase) following RT [7, 37].

The amount of repetitions and sets also differs among the studies of whole body RT. Stone et al. [47] reported that VO_2max significantly improved after three to five sets of RT at 5–10RM. They found that high reps (sets of ten reps) for the first 5 weeks contributed to an improvement of VO_2max. However, other whole body RT studies using even higher reps (15–20RM) did not significantly increase VO_2max following training [11, 34]. Besides the amount of repetitions and sets, the frequency of training may also be an important variable to consider for increasing VO_2max. To illustrate, one study (6 days per week) reported an increase in VO_2max following whole body RT [47], while another study (5 days per week) did not show a significant increase in VO_2max [25, 26]. Therefore, the frequency of training and the volume of work completed do not appear to play a significant role with the increase in VO_2max observed following a whole body or a single exercise RT program.

Effects of rest period between sets

The rest period between RT sets is another important variable to consider because shorter rest periods may result in a greater stimulation of the cardiovascular system, which could potentially influence the change in VO_2max. To illustrate, a study by McCarthy et al. [35] reported an increase in VO_2max following whole body RT with short rest periods (about 75 s). In contrast, another study using shorter rest periods (60 s) [11] observed no significant changes in VO_2max. Therefore, with respect to what is currently known in the literature, the rest period between sets does not appear to be a significant modulating factor for VO_2max. It is conceivable, however, that shorter rest periods (~30 s) may induce a greater cardiovascular demand and thus improve VO_2max. Nevertheless, that is speculative and currently unknown.

Initial VO_2max values

In most RT studies in young subjects, the relative VO_2max at the start of training ranged between 45 and 55 ml/kg/min (Table 1), which are within normal ranges for lean untrained young adults (see the figure reported by Heath et al. [23]). These studies reported that there was no significant change in VO_2max following RT. However, in a few studies, the subjects who had a relatively low VO_2max at the start of the training significantly increased their VO_2max following the RT program. To illustrate, two studies [35, 47] have demonstrated that VO_2max increased 9 and 6 %, respectively, after RT and initial VO_2max were about 39 ml/kg/min in both studies. In addition, Hu et al. [28] reported that VO_2max tended to increase by approximately 8 % following 10 weeks of RT (initial VO_2max was 36 ml/kg/min). These results suggest that VO_2max may increase in young subjects following RT when their initial relative VO_2max is lower than 40 ml/kg/min. Unfortunately, there is no study investigating the dose–response relationship between initial VO_2max and the increase in VO_2max following traditional resistance training; therefore, future research is needed.

Older subjects

Similar to young subjects, whole body RT produced significant increases in muscular strength and muscle mass in older subjects. Additionally, six of nine studies [4, 9, 18, 21, 24, 33, 39, 49, 53] in older subjects have reported significant improvements in VO_2max following RT (Table 2).

Effects of training volume

Eight of nine studies investigated the effects of whole body RT on muscle strength and size as well as VO_2max in older men and women. To illustrate, an earlier study by Frontera et al. [18] examined the effects of whole body RT (three sets at 80 % 1RM, 3 days per week for 12 weeks) on strength and fiber size as well as VO_2max in older male subjects. They reported that knee extension strength and mean fiber area of the vastus lateralis increased 100 and 28 %, respectively, following the training. Furthermore, VO_2max tended to increase by 5 % (0.14 % per session) after the training. On the other hand, Vincent et al. [49] reported that a single set of RT at 80 % 1RM (3 days per week) for 24 weeks elicited significant increases in VO_2max (20 %). These results suggest that training volume is not largely related to the improvement of VO_2max for older people.

Effects of training intensity

One study [49] investigated the effects of different RT intensities on VO_2max in older subjects. Increases in VO_2max were not significantly different (20 and 24 %, respectively) between high-intensity (80 % 1RM) and moderate-intensity (50 % 1RM) groups following 24 weeks of RT. In other older subject studies, it appears that there is no relationship between the intensity of exercise sessions and improvement of VO_2max, which suggests that training intensity (expressed as percent 1RM) may not be an important factor for increasing VO_2max.

Effects of rest period between sets

A study by Lovell et al. [33] reported an increase in VO_2max following incline squat RT with 2-min rest periods between sets. Similar results were reported by Hagerman et al. [21] that VO_2max increased 9 % following 16 weeks of whole body RT (85–90 % of 1RM, three sets) with 2-min rest periods. In contrast, other studies (12 weeks of RT) using similar or relatively shorter rest periods (1.5 to 2 min) [4, 9] observed no significant change in VO_2max. The 1.5- to 2-min rest period between sets does not appear to be a significant modulating factor for VO_2max. As mentioned above, perhaps shorter rest periods (~30 s) may induce a greater cardiovascular demand to improve VO_2max.

Relationship between initial VO_2max at start of the training and its effects

In RT studies, the relative VO_2max at the start of training ranged between 19 and 32 ml/kg/min in older subjects (Table 2) and ranged between 35 and 55 ml/kg/min in

Table 2 Summary of resistance training studies in older subjects

Author	Sex	Age	Subject	Group	Period frequency	Training program	Muscle strength			Muscle size		VO$_2$max (ml/kg/min)			
						Equipment		%	%/S		%	Mode	Baseline	%	%/S
Frontera et al. [17]	M	60–72	Healthy sedentary	RT	12 weeks 3 days/week	80 % 1RM 8 reps 3 sets (M)	KE 1RM	100	2.78	fCSA	28	E	26.9	NS (5)	0.14
Ades et al. [4]	M F	69.9	Healthy	RT	12 weeks 3 days/week	50–80 % 1RM 8 reps 3 sets (M)	KE 1RM	29	0.81	FFM	NS (1)	T	26.0	NS (−4)	−0.11
Hepple et al. [24]	M	65–74	Untrained	RT	9 weeks 3 days/week	6–12RM 3 sets (M)	LP 1RM	58	2.15	fCSA	27	E	27.9	8	0.28
Hagerman et al. [21]	M	63.7	Physically active	RT	16 weeks 2 days/week	85–90 % 1RM 6–8 reps 3 sets (NR)	KE 1RM	50	1.56	FFM	NS (2)	T	31.9	9	0.29
Vincent et al. [49]	M F	66.6	Healthy active	RT-H	24 weeks 3 days/week	80 % 1RM 8 reps 1 set (M)	KE 1RM	15	0.21	–	–	T	20.9	20	0.23
	M F	67.6	Healthy active	RT-L	24 weeks 3 days/week	50 % 1RM 13 reps 1 set (M)	KE 1RM	11	0.15	–	–		20.2	24	0.31
Okazaki et al. [39]	M	64	Physically active	RT	18 weeks 3 days/week	60–80 % 1RM 8 reps 3 sets (M)	KE IsoM	16	0.30	–	–	E	32.6	11	0.20
Wieser et al. [53]	M F	76.2	Healthy untrained	RT	12 weeks 2 days/week	10–15RM 1–4 sets (M)	LP 1RM	38	1.58	–	–	E	19.1	15	0.61
Lovell et al. [33]	M	74	Healthy active	SQ	16 weeks 3 days/week	70–90 % 1RM 6–10 reps 3 sets (M)	SQ 1RM	58	1.21	–	–	E	24.4	7	0.14
Cadore et al. [9]	M	64	Healthy untrained	RT	12 weeks 3 days/week	6–20RM 2–3 sets (M)	KE 1RM	68	1.89	–	–	E	27.3	NS (6)	0.10

M male, *F* female, *RT* whole body resistance training, *SQ* squat training, *KE* knee extension, *RT-H* high intensity resistance training, *RT-L* low intensity resistance training, *1RM* one repetition maximum, *IsoM* isometric, *LP* leg press, *FFM* fat-free mass, *fCSA* fiber cross-sectional area, *NS* not significant, *T* treadmill, *E* ergometer, *%/S* percent change per session, *M* machine, *NR* not reported younger subjects (Table 1). Older subjects in these RT studies have relatively low values compared to corresponding age groups of a previously reported study [23]. Most of these studies in older subjects reported a significant increase in VO_2max following RT, while only three studies in young subjects observed a significant RT-induced increase in VO_2max. We examined the relationship between the initial value of VO_2max at the start of training and the percent change in VO_2max after training using both younger and older subject studies (Fig. 1). There was a significant negative correlation (r=−0.632, p<0.001) between the initial VO_2max and RT-induced change in VO_2max. This result suggests that RT-induced increases in VO_2max are dependent upon the subject's initial VO_2max. The studies using younger subjects found significant increases in VO_2max when the initial VO_2max was lower than 40 ml/kg/min. In older subjects, four studies found that an initial VO_2max value lower than 25 ml/kg/min significantly increased VO_2max following RT. However, older subjects in three other studies who had initial values over 25 ml/kg/min did not significantly increase their VO_2max. In contrast, three studies with subjects having initial values greater than 25 ml/kg/min reported significant increases in VO_2max. The reason for this discrepancy at initial VO_2max values ranging between 25 and 32 ml/kg/min is unknown; however, this gray area represents an equivocal range where VO_2max may or may not be affected by RT. Thus, the RT-induced increase in VO_2max may be elicited when their initial relative VO_2max is lower than 25 ml/kg/min for older subjects and lower than 40 ml/kg/min for younger subjects. Based on a previous study [23], VO_2max declines progressively with age regardless of training status. The VO_2max values of lower than 25 ml/kg/min for older subjects and lower than 40 ml/kg/min for young subjects are about 5 ml/kg/min or more below the average VO_2max values of untrained subjects for each age group (Fig. 2).

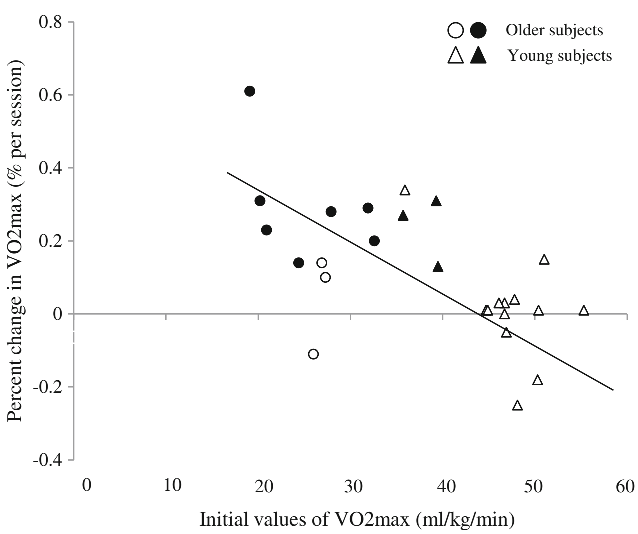

Fig. 1 Relationship between the initial value of VO_2max at the start of resistance training and the percent change in VO_2max after RT using both young and older subject studies. The RT-induced change in VO_2max was expressed as the percent change in VO_2max divided by total training sessions. *Filled symbols* are expressed as significant increases in VO_2max following RT

Possible mechanisms for improving VO_2max by RT

Increases in cardiac output [SVmax and maximal heart rate (HRmax)] and a-vO_2 diff (capillary density and myoglobin concentration of muscle) contribute to the RT-induced improvement of VO_2max. Increases in muscle mass in exercising muscle and blood flow to the exercising muscle are other possible factors that improve VO_2max.

Changes in HRmax and SVmax

Previous RT studies reported that there was no significant change in HRmax at maximal exercise workloads between pre- and post-training [18, 49]. The same results are observed following aerobic exercise training [55]. On the other hand, changes in SV may be responsible for the observed increases in VO_2max, particularly with older adults. Lovell et al. [33] reported a significant increase in SV at 40 W (about 40 % VO_2max) workload following 16 weeks of RT. During exercise, SV increased linearly from pre-exercise values and peaked at 40 % VO_2max, and then SV is maintained during exercise over the 40 % intensity. Although they did not measure at maximal workload, the results of Lovell et al. [33] showed no significant change in SV at both

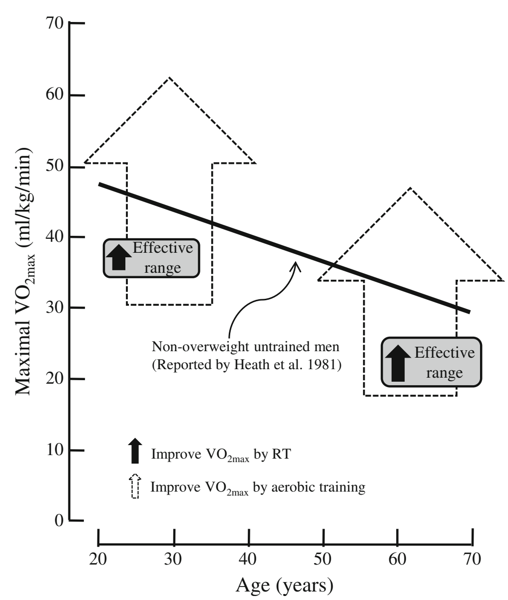

Fig. 2 Schematic illustration of the age-related decline in VO_2max and the RT-induced increase in VO_2max. VO_2max may increase following RT when the initial relative VO_2max is lower than 25 ml/kg/min for older subjects and lower than 40 ml/kg/min for young subjects, which are about 5 ml/kg/min or more below the average VO_2max values of untrained subjects for each age group

50 % VO_2max and 70 % VO_2max between pre- and post-training. Interestingly, that study reported that an important contributor for improving VO_2max is a change in a-vO_2 diff rather than a change in SV.

Change in a-vO_2 diff

The increase in a-vO_2 diff is mainly induced by an increase in capillary density and myoglobin concentration of muscle [12, 22] as well as an increase in muscle mitochondria content and enzyme activity [27]. In addition, changes in peripheral vascular resistance, which is involved in increasing muscular blood flow in working muscle, may contribute to the increase in VO_2max following RT.

Several studies [18, 24] reported RT-induced increases in capillary density and mitochondria enzyme activity in older subjects. To illustrate, Hepple et al. [24] reported that VO_2max increased 7 %, and capillary-to-fiber perimeter exchange index (surface area for exchange between capillaries and muscle fibers) increased 14 % following 9 weeks of RT, and there was a significant correlation between the capillary-to-fiber perimeter exchange index and VO_2max at both baseline and post-training. They concluded that a reduction of the resistance to oxygen flux at the fiber–capillary interface might be an important adaptation for improvement of VO_2max. Frontera et al. [18] also reported RT-induced increases in the capillary-to-fiber ratio and mitochondria enzyme activity following 12 weeks of RT in older men. Thus, RT may improve aerobic capacity in young and old subjects with a low initial VO_2max due to improvements in the capillary-to-fiber ratio and mitochondria enzyme activity.

Another factor affecting the a-vO_2 diff with RT may be blood flow to the exercising muscle. Compared to young healthy men, leg blood flow is lower in trained middle-aged men during submaximal and near maximal levels of exercise [50]. The decline in local circulation in exercising muscle may contribute to changes in VO_2max with age. Recently, Phillips et al. [40] reported that 20 weeks of RT improved age-related declines in leg blood flow and vascular conductance after acute exercise. The magnitude of increase in leg blood flow after the exercise was similar between young and old subjects. The improvement of blood flow in exercising muscle may contribute to the RT-induced increase in VO_2max.

Changes in muscle mass

Previous RT studies reported that fat-free mass (FFM) increased ~2 kg following 8–12 weeks of training [15, 20, 21]. It is presumed that approximately half of the increased FFM is skeletal muscle mass [2]. During arm cranking or treadmill running, VO_2max divided by exercising muscles is about 200 ml/min/kg muscle mass [43]. Thus, increasing 2 kg FFM (about 1 kg skeletal muscle mass) contributes to a change in VO_2max (about 200 ml/min). Although FFM increased after RT, a significant increase in VO_2max was only observed in older subjects [21] and was undetected in young subjects [15, 20]. The RT-induced increase in muscle mass may therefore contribute to only a small improvement of VO_2max.

Conclusion

It is an undeniable fact that resistance training is a potent stimulus for muscle hypertrophy and strength gain. This training also elicits an improvement of VO_2max when the initial VO_2max at start of the training is lower compared to average values of VO_2max for the corresponding age. The RT-induced increase in VO_2max may be associated with an improvement in the ability of oxygen to be utilized in hypertrophied muscles. Thus, RT can be expected to improve concurrently both muscular (muscle hypertrophy and functional ability) and cardiovascular (VO_2max) fitnesses within a single mode of resistance training when young and old persons have initially low fitness levels. Unfortunately, there is no study investigating the dose–response relationship between initial VO_2max and the increase in VO_2max following traditional resistance training; therefore, future research is needed.

Conflict of interest The authors have nothing to disclose. The authors have no financial or other conflicts interest.

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