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Cycle training induces muscle hypertrophy and strength gain: strategies and mechanisms (Review)

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Cycle training is widely performed as a major part of any exercise program seeking to improve aerobic capacity and cardiovascular health. However, the effect of cycle training on muscle size and strength gain still requires further insight, even though it is known that professional cyclists display larger muscle size compared to controls. Therefore, the purpose of this review is to discuss the effects of cycle training on muscle size and strength of the lower extremity and the possible mechanisms for increasing muscle size with cycle training. It is plausible that cycle training requires a longer period to significantly increase muscle size compared to typical resistance training due to a much slower hypertrophy rate. Cycle training induces muscle hypertrophy similarly between young and older age groups, while strength gain seems to favor older adults, which suggests that the probability for improving in muscle quality appears to be higher in older adults compared to young adults. For young adults, higher-intensity intermittent cycling may be required to achieve strength gains. It also appears that muscle hypertrophy induced by cycle training results from the positive changes in muscle protein net balance.

Keywords: aerobic exercise, muscular adaptation, lower body, cycling, ergometer

Endurance training is a major part of any exercise program seeking to improve aerobic capacity and cardiovascular health. Another major part of exercise programming is strength/resistance training, which improves muscle morphology. Thus to improve muscular strength and cardiovascular fitness in young, middle-aged and older populations, the American College of Sports Medicine recommends combining training intensity, volume, and frequency to optimize muscle hypertrophy and strength gain as well as aerobic capacity ($\dot{V}O_2$max) (23). However, the vigorous training intensity and/or high training frequency might hinder some older adults from participating in this type of training program. Interestingly, recent studies have reported concurrent improvements in $\dot{V}O_2$max and muscle hypertrophy in young and older populations after single exercise training (27, 62, 64, 65). These single exercise modes include ambulatory exercise (walking, jogging, and running), cycling, and swimming.

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Recently, we have summarized whether or not ambulatory exercise produces muscle hypertrophy and strength gain in the lower extremities (65). According to the literature, it seems that relatively long periods, over half a year, of walking and jogging can increase leg muscle size among older adults. However, competitive marathon running and regular high-intensity distance running may not produce leg muscle hypertrophy in young and middle-aged adults, which might be related to insufficient recovery from the muscular damage caused by repeated eccentric contractions during running. Meanwhile, cycling exercise involves mainly concentric contractions and therefore muscular damage is lower in cycling compared with running (59). With respect to muscle damage, cycle training may therefore be better suited for improving muscle size and function compared to running.

To discuss the effect of cycle training on muscle size and strength, cross-sectional and longitudinal studies have been used. In cross-sectional studies, it is known that professional cyclists have larger thigh muscle size compared to controls (36, 52). Hug et al. (36) have shown that total thigh muscle cross-sectional area (CSA), especially vastus lateralis (VL) and biceps femoris (BF) muscle CSA, is larger for professional cyclists than for recreationally-active sport science students. Maximum isometric strength of knee extension is greater in track sprint cyclists than in untrained subjects (52). In addition, both fast- (FT) and slow-twitch (ST) muscle fiber areas in VL are larger in cyclists than that of untrained subjects (25, 52). It is unclear, however, whether the greater muscle size and strength were induced exclusively by cycle training because elite cyclists perform other types of exercise training such as resistance training. Moreover, the influence of genetic factors may have also confounded the observed differences. Unfortunately, it is difficult to differentiate the effect of cycle training on muscle size and strength from these confounding factors with a cross-sectional study design. Therefore, the results of training studies employing untrained subjects needs to be reviewed.

A training intensity of more than 60% of one's concentric repetition maximum (1RM) is commonly considered as the minimum intensity required to achieve muscle hypertrophy under work matched conditions (23). However, in recent years, it has been established that, when performed repetitively or until volitional failure, a low exercise intensity such as 30% 1RM can lead to an increase in myofibrillar protein synthesis (9). These results suggest that high external loads are not a prerequisite for increasing muscle protein synthesis or muscle size (60). Peak muscular activation in VL and vastus medialis (VM) during cycling corresponded to approximately 50% of maximum voluntary contraction (MVC) (19). Therefore, cycle training that consists of repetitive movements may suffice as a minimum stimulus required to increase muscle protein synthesis. In fact, previous studies have shown that protein synthesis acutely (28) and chronically (77) can be stimulated by cycling in untrained subjects. Furthermore, muscle hypertrophy by cycle training is frequently observed when cycle training has been performed for relatively long periods (24, 58, 62). Thus, it is plausible that cycle training does not increase muscle size during short periods (34, 35) but that cycle training requires relatively long periods to induce significant muscle hypertrophy (5, 58).

The primary purpose of this review is to discuss the effect of cycle training on muscle size and strength of the lower extremity, especially thigh muscle mainly activated during pedaling, with three groups of subjects: untrained and healthy young adults, older adults and patients. Furthermore, we also discuss the possible mechanism of muscle hypertrophy induced by cycle training.

Methods

Literature search

Typical online search using MEDLINE, Web of Science and SPORTDiscuss was performed with the following keywords to obtain relevant articles: ‘endurance training’, ‘cycling’, ‘cycle’, ‘ergometer’, ‘training’, ‘muscle’, ‘muscle strength’, ‘muscle size’, ‘muscle cross-sectional area’, ‘protein synthesis’, ‘concurrent resistance and endurance training’, ‘concurrent strength and aerobic training’, ‘combined resistance 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

To be included, a study needed to meet the following criteria: (a) Study population: Subjects were untrained healthy young (20–40 years) and older (more than 60 years) adults and untrained patients (more than 20 years) defined as individuals with a cardiovascular and/or muscular disease. Young and older adults could be physically active but could not be participating in regular strength and endurance training. (b) Outcome measures: The study needed to investigate whole muscle size, muscle fiber size, fat-free mass (FFM) and/or muscle strength (1RM, isokinetic and/or isometric strength). FFM and muscle volume estimated by skinfold measurements were excluded. (c) Language: The search was limited to original research that was written in English. Furthermore, to investigate the effect of typical cycle training on muscle size and strength, studies were excluded if cycling was performed with one-leg. Studies were also excluded if cycle training was combined with other interventions such as nutritional and/or blood flow restriction to an exercised muscle. We also discuss the possible mechanism of muscle hypertrophy induced by cycle training, including the articles which were not collected by means of the aforesaid online search procedures.

Analysis of effect size

Analysis of effect size was performed by reference to previous studies (73, 89) to investigate the magnitude of muscle hypertrophy and strength gain with cycle training. Effect size (ES) was calculated with the following formula: [(posttest mean – pretest mean) / pretest standard deviation], using the data of the searched articles which clearly demonstrated pretest and posttest mean and standard deviation (SD) or standard error (SE) in terms of muscle size and strength. When only SE was reported, SD was calculated from the SE. Differences of ES among the three subject groups and within training design variables (less than vs. more than 40 training sessions, continuous vs. interval training) were evaluated with one-way ANOVA and unpaired *t*-test, respectively. Statistical significance was set at $p \leqq 0.05$.

Changes in muscle size and strength induced by cycle training

Overall effect size for muscle hypertrophy and strength gain

The ES is presented in Table I and Fig. 1. The 31 ESs for lower limb muscle hypertrophy and 22 ESs for lower body strength development were obtained from 39 studies. The mean ES for muscle hypertrophy was 0.40 (95% confidence interval [CI]: 0.10, 0.71; the number of ESs [*n*]: 18) for young adults, 0.28 (95% CI: –0.31, 0.87; *n*: 6) for older adults and 0.69 (95% CI: –0.07, 1.44; *n*: 7) for patients. A significant difference was not found among the three groups. Meanwhile, the mean ES for strength gain was 0.16 (95% CI: –0.06, 0.39; *n*: 12) for young adults, 0.49 (95% CI: –0.01, 1.00; *n*: 4) for older adults and 0.21 (95% CI: 0.03, 0.39; *n*: 6) for patients. Although the value of the older adults tended to be higher compared to the other two groups, a significant difference was not found among the three groups.

Table I. Effect size for muscle hypertrophy

	Overall		**Number of training sessions**				
			< 40		**40 ≦**		
	Mean (95% CI)	***N***	**Mean (95% CI)**	***N***	**Mean (95% CI)**		***N***
Young (Y)	0.40 (0.10, 071)	18	0.21 (–0.13, 0.54)	13	0.91 (0.34, 1.48)	*	5
Older (O)	0.28 (–0.31, 0.87)	6	ID		0.41 (–0.63, 1.45)		4
Y+O	0.37 (0.12, 0.62)	24	0.18 (–0.11, 0.47)	15	0.69 (0.24, 1.13)	*	9
Patient (P)	0.69 (–0.07, 1.44)	7	0.63 (–0.32, 1.59)	5	ID		
Y+O+P	0.44 (0.20, 0.68)	31	0.29 (0.01, 0.58)	20	0.71 (0.27, 1.15)		11

CI: confidence interval; N: number of effect sizes; ID: insufficient data (< 4 Effect sizes); * $p < 0.05$, vs < 40

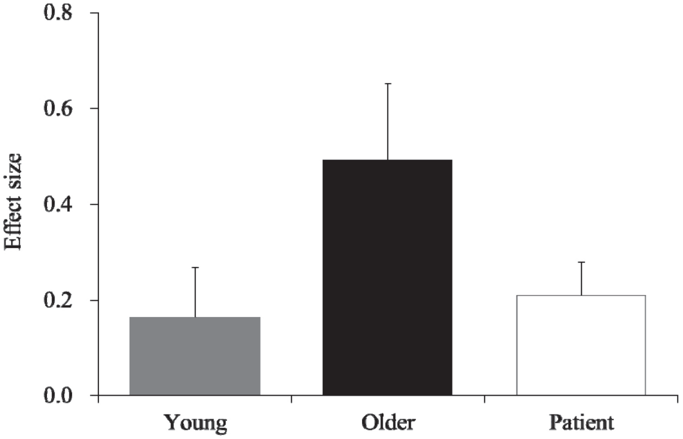

Fig. 1. Effect size for lower body strength gain

Untrained young adults

With respect to the probability of muscle hypertrophy in young adults, 8 out of 22 studies evaluating muscle size have reported that cycle training induced thigh muscle hypertrophy at the whole muscle level and/or muscle fiber level for young adults. It is suspected that training design variables could be the key determinants for these hypertrophic effects. One study has shown that muscle fiber hypertrophy was observed in cycle training at 75–85% HRmax for 30–60 min, 4 days per week, (62) whereas another study demonstrated no muscle hypertrophy with cycle training at an exercise intensity varying from the ventilatory threshold to 90% VO_2max for 21–42 min, 3 days per week (5). There were not large differences in exercise intensity, duration and frequency between the previous two studies but the program period of the former was approximately two times longer than that of the latter. As summarized in

Table II, muscle hypertrophy is more likely to take place when the training period or the total number of training sessions is greater. Moreover, this trend is kept consistent regardless of the exercise protocol used, although the previous studies investigating the effect of cycle training on muscle size are broadly divided into two types: continuous or interval training. For continuous cycling, 2 of 9 studies with less than 40 training sessions have shown muscle hypertrophy at the whole muscle or muscle fiber level, while 3 of 4 studies with equal to or more than 40 training sessions have observed it. Muscle fiber area tended to increase in both ST (17%, ES: 2.09) and FTa (11%, ES: 0.77) fibers in the only study without muscle hypertrophy (15). Meanwhile, for interval cycling, both studies with equal to or more than 40 training sessions have shown muscle hypertrophy but no studies with less than 40 training sessions have observed significant changes. Therefore, program period would appear to be the key determinant for the probability of muscle hypertrophy with cycle training in young adults. Meanwhile, similar to the probability of muscle hypertrophy, program period appears to be the key determinant for the magnitude of change. The mean ES for muscle hypertrophy in previous studies with less than 40 training sessions was 0.21 (95% CI: –0.13, 0.54; *n:* 13), whereas that with equal to or more than 40 training sessions was 0.91 (95% CI: 0.34, 1.48; *n:* 5), and the value of the latter was significantly higher than that of the former.

To better determine the reason why cycle training requires a relatively longer period of training until increases in muscle size are observed, we compared the magnitude of muscle hypertrophy between cycle and resistance training. Mikkola et al. (58) compared the percentage of muscle hypertrophy between resistance training, continuous cycle training and the combination of both. As a result, muscle CSA of the quadriceps femoris significantly increased by 6% for the resistance training group and only by 2% for the cycle training group after the same training period (42 training sessions). In other words, the magnitude of muscle hypertrophy with cycle training appears to be one third of that of resistance training. However, the calculation of percentage increases cannot be accurately compared either within or across research studies because percent change does not take into consideration the variance of muscle hypertrophy among subjects (73). Therefore, we calculated the ES for muscle hypertrophy with the previous data of McCarthy et al. (57) and Bell et al. (5). The ES was 0.56–1.17 for lower body resistance training whereas only 0.16–0.39 for continuous cycle training despite a similar training period and frequency. Therefore, it is plausible that cycle training requires a longer training period than typical resistance training until significant increases in muscle size can be observed because of a much slower hypertrophy rate. It is also possible and likely that there are differences in the intrinsic muscular environment between resistance and cycle training such that although increases in muscle size occur with cycling, those changes may never reach the magnitude observed with resistance training.

In addition to the probability of muscle gain for young adults, significant increases were observed in 1RM and/or isokinetic and/or isometric strength in 4 out of 11 studies. This is similar to that found for changes in muscle size. However, the key determinant for the strength gain is unlikely to be identical to that of muscle hypertrophy. While the occurrence of muscle hypertrophy depends on the program period or the total number of training sessions, strength gain following cycle training is more likely to be influenced by the exercise type and intensity. In previous studies evaluating muscle strength, 3 out of 4 studies using maximal or submaximal interval cycling resulted in strength gain in the lower limb muscle. However, with continuous cycling, this adaptation was observed only for 1 out of 7 studies using continuous cycling. Therefore, it appears that exercise intensity or effort, rather than the training period, is the key factor for strength gain after cycle training in untrained young

Table II. The effects of cycling training on muscle size and strength as well as VO_2max in untrained young adults

Author	Sex (Age)	Period frequency (sessions)	Training	Body mass	Muscle strength (%)						Muscle size (%)					$\dot{V}O_2$max (%)
					1RM		Isokinetic		Isometric		mCSA		mfCSA (VL)		FFM (DEXA)	
Continuous cycling																
LaStayo et al. 2000 (45)	M (24)	8 wk 2–5 d/wk (28)	54–65% HRpeak 15–30 min	—					KE	ns				ns		ns (–10)
Hoppeler et al. 1985 (34)	M F (28)	6 wk 5 d/wk (30)	maximal maintained power 30 min	ns										ns (–3)		14
Howald et al. 1985 (35)	M F (29)	6 wk 5 d/wk (30)	72% $\dot{V}O_2$max 30 min	—									I II A II B	ns ns ns		14
McCarthy et al. 1995, 2002 (56, 57)	M (27)	10 wk 3 d/wk (30)	70% HRR 45 min	ns (–2)	SQ	ns (–1)	KE	ns (–5)	KE	ns (–2)	QF	3	I II	ns (4) ns (5)		18
Andersen et al. 1977 (2)	M (21)	8 wk 4 d/wk (32)	80% $\dot{V}O_2$max 40 min	ns (1)									I II A II B	ns (20) 17 28		16
Carter et al. 2001 (12)	M (22)	7 wk 5 d/wk (35)	60% $\dot{V}O_2$max 60 min	ns (0)									ST FT	ns (31) ns (19)	ns (0)	17
	F (22)			ns (–1)										ns (16) ns (3)	ns (0)	30
Tarnopolsky et al. 2007 (84)	M (24)	7 wk 5 d/wk (35)	60% $\dot{V}O_2$max 1 hour	ns (0)											ns (0)	9
	F (22)			ns (–1)											ns (0)	14
Bell et al. 2000 (5)	M F (22)	12 wk 3 d/wk (36)	VT–90% $\dot{V}O_2$max 21–42 min	—	KE	ns (3) ns (14)							I II	ns (11) ns (11)		5 13

Table II. (cont.)

Author	Sex (Age)	Period frequency (sessions)	Training	Body mass	Muscle strength (%)						Muscle size (%)					$\dot{V}O_2$max (%)
					1RM		Isokinetic		Isometric		mCSA		mfCSA (VL)		FFM (DEXA)	
Putman et al. 2004 (72)	M (23) F (22)	12 wk 3 d/wk (36)	VT–90% $\dot{V}O_2$max 21–42 min	—									I II A	ns ns		—
Parcell et al. 2009 (66)	M (23)	12 wk 3 d/wk (36)	60–80% $\dot{V}O_2$max 30–90 min	—	LP KE	ns ns										12
Kaljumae et al. 1994 (41)	M (22)	10 wk 4 d/wk (40)	35–70% maximal load 30 min	—					KE	SD						9
Mikkola et al. 2012 (58)	M (37)	21 wk 2 d/wk (42)	A Aer–AnT 30–90 min	ns (1)	KE	ns(1)			KE	ns(4)	QF	2				5
Denis et al. 1986 (15)	M (22)	20 wk 4 d/wk (80)	70–80% $\dot{V}O_2$max 60 min										ST FTa	ns (17) ns (11)		15
Nelson et al. 1990 (62)	M (30)	20 wk 4 d/wk (80)	75–85% HRmax 30–60 min	ns (–3)			KE	14					I II A II B	20 11 8		20
Gollnick et al. 1973 (24)	M (28–40)	20 wk 4 d/wk (80)	75–90% $\dot{V}O_2$max 1 hour	—									ST FT	23 ns (–8)		13
Interval cycling																
Allemeier et al. 1994 (1)	M (23)	6 wk 2–3 d/wk (15)	75 g/kg TBM 3×30 s supramaximal sprint	ns (0)									I II A II B	ns (6) ns (12) ns (12)		13
Jacobs et al. 1987 (39)	M F (22)	6 wk A 2.5/wk (A 15)	75 g/kg body weight 2–6×15 s + 2–6×30 s maximal sprint	—									ST FT	ns (10) ns (6)		—

Table II. (cont.)

Author	Sex (Age)	Period frequency (sessions)	Training	Body mass	Muscle strength (%)						Muscle size (%)					$\dot{V}O_2$max (%)
					1RM		Isokinetic		Isometric		mCSA		mfCSA (VL)		FFM (DEXA)	
Busko et al. 2008 (10)	— 22	4 wk 4 d/wk (16)	5 maximal efforts loads equal 10% of body weight	—					HE KE	7 ns (2)						—
	— 23		5 maximal efforts loads equal 5% of body weight	—						7 7						—
	— 23		5×3 min 250 W, 80 rpm	—						ns (3) ns (–5)						—
	— 23		5×3 min 250 W, 45 rpm	—						ns (5) ns (5)						—
Harridge et al. 1998 (29)	M (22)	6 wk 4 d/wk (24)	6% of body mass 3×3–s maximal sprints 8–16 sets	—					KE	7				ns (7)		—
Linossier et al. 1993 (47)	M F (22)	7 wk 4 d/wk (28)	2×8–13×5 s maximal sprint	1							TH R L	 ns (3) ns (–1)	ST FT	–11 ns (–6)		ns (–1)
Tabata et al. 1990 (83)	M (23)	7 wk 5 d/wk (35)	90% $\dot{V}O_2$max 500 kcal/d	—			KE /CSA	18			QF	ns (–6)				10
Linossier et al. 1997 (48)	M (20)	10 wk 4 d/wk (40)	8% of body mass 2×15×5 s maximal sprint	ns (2)							Ex VL	6 5	ST FTa FTb	ns (9) ns (16) 45		—
Sleivert et al. 1995 (79)	M (20–28)	14 wk 3 d/wk (42)	65 g/kg of body mass 2–4×4–5×10 s maximal sprint	ns (1)			KE LP	ns ns					I II	SI SI		—

Table II. (cont.)

Author	**Sex (Age)**	**Period frequency (sessions)**	**Training**	**Body mass**	**Muscle strength (%)**						**Muscle size (%)**					**$\dot{V}O_2$max (%)**
					1RM		**Isokinetic**		**Isometric**		**mCSA**		**mfCSA (VL)**		**FFM (DEXA)**	
Others (Continuous + interval training)																
Farup et al. 2012 (20)	M (23)	10 wk 3 d/wk (30)	(1) 60–75% of WM 30–45 min (2) 70–80% of WM 2×20 min (3) 80–90% of WM 8×4 min	ns	LP	SI			KE KF	ns ns	TH	ns		ns		SI
Simoneau et al. 1985 (78)	M F (19–30)	15 wk 4–5 d/wk (60)	(1) continuous (2) 10–15×15–30 s (3) 4–5×60–90 s	—									I II A II B	21 ns (12) 24		—

M: male, F: female, m: muscle, mf: muscle fiber, TBM: total body mass, VT: ventilatory threshold, $\dot{V}O_2$max: maximal oxygen uptake, HRmax: maximal heart rate, HRR: heart rate reserve, WM: watt-max, KE: knee extension, KF: knee flexion, LP: leg press, SQ: squat, HE: hip extension, QF: quadriceps femoris, CSA: cross-sectional area, VL: vastus lateralis, Ex: extensor, TH: thigh, R: right, L: left, I: type I, II: type II, AerT: aerobic threshold, AnT: anaerobic threshold, FFM: fat-free mass, DEXA: dual energy X-ray absorptiometry, 1RM: one repetition maximum, ST: slow-twitch fibers, FT: fast-twitch fibers, ns: not significant, A: about, SI: significant increase, SD: significant decrease subjects. Furthermore, we compared the mean ES for strength gain between both types of training to better determine the differences in the magnitude of strength development. As a result, the ES was 0.19 (95% CI: –0.17, 0.56; *n*: 7) for continuous training, whereas 0.13 (95% CI: –0.30, 0.56; *n*: 5) for interval training. Significant differences were not found between both types. Therefore, in young adults, the magnitude of strength gain with cycle training is low and might not necessarily differ between two types though further studies are needed to verify this because of the small number of ESs.

Untrained older adults

With respect to the probability of muscle hypertrophy in older adults, 4 out of 8 studies evaluating muscle size have shown thigh muscle hypertrophy at the whole muscle and/or muscle fiber level in untrained older adults. In agreement with young adults, the increase in muscle size in older subjects consistently occurred more when the total number of training sessions was high. As summarized in Table III, for continuous cycle training, all 4 studies with less than 40 training sessions showed no muscle hypertrophy, but 2 out of 3 studies with more than 40 training sessions observed muscle hypertrophy. For interval cycle training, both studies with over 40 training sessions have shown a significant increase in muscle fiber area. No studies were found that used less than 40 training sessions. The probability of muscle hypertrophy after cycle training tended to be higher for older adults compared to young adults. However, it is unlikely that this difference resulted from physiological variance. Simply, there are so many studies that used less than 40 training sessions for young subjects that the probability of muscle hypertrophy is reduced. Indeed, of the searched articles, 5 out of 8 older adult studies used the total number of training sessions equal to or more than 40, while only 7 out of 22 young subject studies satisfied this number. Meanwhile, similar to the probability of muscle hypertrophy, program period might also be the key determinant for the magnitude of change. When the ESs of both young and older adults were pooled together because of insufficient data within older adults to draw conclusions based on age, the mean ES for muscle hypertrophy in studies with equal to or more than 40 training sessions (ES: 0.69; 95% CI: 0.24, 1.13; *n*: 9) was significantly higher than that with less than 40 training sessions (ES: 0.18; 95% CI: –0.11, 0.47; *n*: 15). Also, the ES was 0.91 (95% CI: 0.34, 1.48; *n*: 5) in young adult studies with equal to or more than 40 training sessions, whereas 0.41 (95% CI: –0.63, 1.45; *n*: 4) in older adult studies with it, and a significant difference was not found between both age groups. Therefore, as long as the total number of training sessions exceeded 40, the magnitude of hypertrophy with cycle training between young and older age groups appears similar, although this needs to be verified with more studies.

Regarding the probability of strength gain in older adults, a significant increase was observed in 1RM and/or isokinetic and/or isometric strength in 7 out of 8 studies evaluating muscle strength. The probability of strength gain after cycle training is higher in older adults than in young adults. Unlike young adults, most of the studies that used continuous cycle training showed significant strength gain in older adults as summarized in Table III. This suggests that significant muscle strength gain can be achieved regardless of exercise type or intensity for untrained older adults. Furthermore, the mean ES for strength gain in older subjects (ES: 0.49; 95% CI: –0.01, 1.00; *n*: 4) was approximately three times higher than that in young subjects (ES: 0.16; 95% CI: –0.06, 0.39; *n*: 12). Therefore, it appears that strength gain favors older adults. It is unclear whether these findings suggest a physiologic difference with age or if the difference in strength may partially be explained by an attenuated baseline strength test due to an inability to maximally produce force under novel conditions such as

Table III. The effects of cycling training on muscle size and strength as well as VO_2max in untrained older adults

Author	Sex (Age)	Period frequency (sessions)	Training	Body mass	Muscle strength (%)						Muscle size (%)						$\dot{V}O_2$max (%)
					1RM		Isokinetic		Isometric		mCSA		mfCSA (VL)		FFM (DEXA)		
Continuous cycling																	
Freyssenet et al. 1996 (22)	M (63)	6 wk 4 d/wk (24)	70–80% HRmax 60 min	ns (0)									I II a II b	ns (1) ns (–3) ns (–8)			6
Izquierdo et al. 2004 (37)	M (68)	16 wk 2 d/wk (32)	70–90% HRmax 30–40 min	ns (0)	SQ	11					QF	ns (4)					—
Cadore et al. 2010 (11)	M (64)	12 wk 3 d/wk (36)	80–100% VT_2 A 20–30 min	ns (–1)	KE	25			KE	ns							20
Ferketich et al. 1998 (21)	F (69)	12 wk 3 d/wk (36)	70–80% $\dot{V}O_2$peak 30 min	ns (1)									I II A II B	ns (–1) ns (3) ns (17)			24
Harber et al. 2009 (27)	F (71)	12 wk 3.5 d/wk (42)	60–80% HRR 20–45 min	ns (–1)					KE	35	QF MV	12	I II a	16 ns			30
Lovell et al. 2010 (50)	M (75)	16 wk 3 d/wk (48)	50–70% $\dot{V}O_2$max 30–45 min	–3	SQ	18									UL	7	15
Hepple et al. 1997 (33)	M (68)	18 wk 3 d/wk (54)	70–80% HRR 30 min	–5										ns (–5)			23
Okazaki et al. 2002 (63)	M (64)	18 wk 3 d/wk (54)	50–80% $\dot{V}O_2$max 60 min	ns (–1)					KE	13							20

Table III. (cont.)

Author	Sex (Age)	Period frequency (sessions)	Training	Body mass	Muscle strength (%)						Muscle size (%)						$\dot{V}O_2$max (%)
					1RM		Isokinetic		Isometric		mCSA		mfCSA (VL)		FFM (DEXA)		
Strasser et al. 2009 (81)	M F (76)	24 wk 3 d/wk (72)	60% $\dot{V}O_2$max 15–40 min	ns (1)	LP	ns (11)											ns(6)
Interval cycling																	
Verney et al. 2006, 2008 (85, 86)	M (73)	14 wk 3 d/wk (42)	1 min (75–85% HRmax) 4 min (80–95% HRmax) 10–12 min×3 sets	ns (–2)			KE	12	KE	13	QF H	ns (2) ns (0)	I II a	ns (8) 13			10
Charifi et al. 2003 (13)	M (73)	14 wk 4 d/wk (56)	1 min (85–95% HRmax) 4 min (65–75% HRmax) 5 min×9 sets	—									I II a	ns (6) 23			14
Other																	
Macaluso et al. 2003 (51)	F (69)	16 wk 3 d/wk (48)	40% of 2 RM 8 sets×16 PR	ns					KE LP	SI SI							—
			80% of 2 RM 8 sets×8 PR	ns						SI SI							—
			(1) 40% of 2 RM 4 sets×16 PR + (2) 80% of 2 RM 4 sets×8 PR	ns						SI SI							—

M: male, F: female, m: muscle, mf: muscle fiber, VT_2: second ventilatory threshold, $\dot{V}O_2$max: maximal oxygen uptake, HRmax: maximal heart rate, HRR: heart rate reserve, RM: revolutions maximum, PR: pedal revolutions, KE: knee extension, LP: leg press, SQ: squat, QF: quadriceps femoris, H: hamstrings, MV: muscle volume, CSA: cross-sectional area, VL: vastus lateralis, I: type I, II: type II, FFM: fat-free mass, DEXA: dual energy X-ray absorptiometry, UL: upper leg, 1RM: one repetition maximum, ns: not significant, SI: significant increase

Table IV. The effects of cycling training on muscle size and strength as well as VO_2max in patients

Author	Sex (Age)	Subject	Period frequency (sessions)	Training	Body mass	Muscle strength (%)						Muscle size (%)				$\dot{V}O_2$peak (%)
						1RM		Isokinetic		Isometric		mfCSA (VL)		FFM		
Continuous cycling																
Petersen et al. 2009 (67)	M F (42)	hemodialysis	6 wk 3 d/wk (18)	50–80% $\dot{V}O_2$peak 20 min	ns (0)			KE	ns	KE	ns					ns (2)
Steiner et al. 2004 (80)	M (56)	coronary artery disease	8 wk 3d/wk (24)	~60% $\dot{V}O_2$peak 30 min	—			KE	ns	KE	ns		19	DEXA	3	—
Pitta et al. 2004 (69)	M F (64)	chronic obstructive pulmonary disease	8 wk 3d/wk (24)	80% HRpeak 30 min	—									imped-ance	ns (0)	—
Belardinelli et al. 1995 (4)	M F (56)	chronic heart failure	8 wk 3 d/wk (24)	40% $\dot{V}O_2$peak 30 min	—							I II	24 17			17
Haykowsky et al. 2005 (32)	F (72)	chronic heart failure	12 wk 2 d/wk (24)	60–70% HRR 15–45 min	—	LP	13									12
Lee et al. 2008 (46)	M F (67)	stroke	10–12 wk 3 d/wk (30)	50–70% $\dot{V}O_2$peak 30 min	—	LB	ns (3)									12
Kiilavuori et al. 2000 (42)	M (52)	chronic heart failure	12 wk 3 d/wk (36)	50–60% $\dot{V}O_2$peak 30 min	—					KE	ns	ST FT	ns (10) ns (9)			—
Preisler et al. 2009 (71)	— (56)	Kennedy disease	12 wk 2–5 d/wk (42)	65–70% $\dot{V}O_2$max 30 min	—					KE HE	ns (1) ns (–5)			DEXA	ns (–1)	ns

Table IV. (cont.)

Author	Sex (Age)	Subject	Period frequency (sessions)	Training	Body mass	Muscle strength (%)						Muscle size (%)				$\dot{V}O_2$peak (%)
						1RM		Isokinetic		Isometric		mfCSA (VL)		FFM		
Sveen et al. 2008 (82)	M (32)	Becker muscular dystrophy	12 wk ~5 d/wk (50)	65% VO_2max 30 min	ns (–1)					KE HE	ns (5) ns (2)	I II	ns (39) ns (42)	DEXA	ns (–1)	SI
Interval cycling																
Bouchla et al. 2011 (7)	M F (51)	chronic heart failure	12 wk 3 d/wk (36)	~40 min (1) 30 sec: 50% Wpeak (2) 60 sec: rest	—	KE 2 RM	10							DEXA	ns (1)	8
Delagardelle et al. 2002 (14)	M (60)	congestive heart failure	12 wk 3–4 d/wk (40)	40 min (1) 2 min (50% VO_2peak) (2) 2 min (75% VO_2peak)	ns (–1)			KE KF	3 11							ns (0)
El Mhandi et al. 2008 (18)	M (20–44)	Charcot–Marie–Tooth	24 wk 3 d/wk (72)	6×5 min (1) 4 min (40% Pmax) (2) 1 min (Pmax)	—			KE KF	10 13	KE KF	ns (2) ns (4)					10

M: male, F: female, m: muscle, mf: muscle fiber, $\dot{V}O_2$max: maximal oxygen uptake, $\dot{V}O_2$peak: peak oxygen uptake, HRpeak: peak heart rate, HRR: heart rate reserve, Pmax: maximal aerobic power, Wpeak: peak workload, KE: knee extension, KF: knee flexion, HE: hip extension, LP: leg press, LB: lower body, CSA: cross-sectional area, VL: vastus lateralis, I: type I, II: type II, FFM: fat-free mass, DEXA: dual energy X-ray absorptiometry, 1RM: one repetition maximum, ST: slow-twitch fibers, FT: fast-twitch fibers, ns: not significant, SI: significant increase exercise (e.g. fear of injury). Meanwhile, in the only study without strength gain after continuous cycle training, training intensity was constant throughout the training period, while in the other studies observing significant strength gain gradually increased exercise training intensity over the training period. This suggests that it is important that workload is adjusted to maintain sufficient mechanical stress to skeletal muscle.

Patients

Generally, fitness levels are lower in patients compared to healthy adults because of lower levels of daily activity, which may influence muscle adaptations to cycle training. Therefore, we will discuss the effect of cycle training on muscle size and strength for patients separately from healthy adults (Table IV). With respect to the probability of muscle hypertrophy, 2 out of 4 studies evaluating muscle size have shown muscle fiber hypertrophy of the VL after continuous cycle training in patients. In patients, muscle hypertrophy following cycle training appears to be influenced more by the initial value rather than training design variables. Both type I and type II fiber size significantly increased after 8 weeks of continuous cycle training even at an exercise intensity of 40% $\dot{V}O_2$peak (4) but did not change after 12 weeks of cycle training at 50–60% $\dot{V}O_2$peak (42) in patients with chronic heart failure. Thus, a longer training period and a higher exercise intensity do not necessarily contribute to muscle fiber hypertrophy after continuous cycle training in patients. Meanwhile, with respect to initial level of muscle size, muscle fiber area was much lower in both studies observing an increase in muscle size (approximately 2500–4000 μm^2) (4, 80) compared to the other 2 studies where no change in muscle size occurred (approximately 4000–6000 μm^2) (42, 82). Therefore, it appears that muscle fiber hypertrophy is observed especially in patients with lower muscle fiber area. Furthermore, the mean ES tended to be higher in patients (ES: 0.69; 95% CI: –0.07, 1.44; *n*: 7) compared to untrained healthy young (ES: 0.40; 95% CI: 0.10, 0.71; *n*: 18) and older (ES: 0.28; 95% CI: –0.31, 0.87; *n*: 4) adults, which may be also related to lower muscle size for patients compared to healthy adults. Meanwhile, to the best of our knowledge, there is no study evaluating whole muscle size measured by MRI and CT in patients before and after cycle training. Future research needs to determine whether cycle training elicits muscle hypertrophy at the whole muscle level in patients.

Regarding the probability of strength gain, only 1 out of 7 previous studies using continuous cycle training have shown increased strength in patients, whereas strength gain was observed in all 3 studies using interval training. Interval cycle training could result in a greater training stimulus to the exercising muscle because interval training allows patients to exercise for longer total periods of time at a higher exercise intensity (74). Therefore, it appears that interval cycle training may be more suitable to improve muscle strength in patients than continuous cycle training. One of the reasons that significant strength gain is frequently observed in continuous training for older adults may be the lower initial value of strength compared to young adults. Thus, even continuous cycle training is likely to induce significant strength gain for patients because they generally have lower values of strength compared to untrained healthy adults. However, continuous cycle training does not appear to be an effective method for strength gain in patients. For example, the mean ES for strength gain tended to be lower in patients (ES: 0.21; 95% CI: 0.03, 0.39; *n*: 6) compared to older adults (ES: 0.49; 95% CI: –0.01, 1.00; *n*: 4). In contrast to older adults, patients may not increase strength after continuous training for several reasons. To illustrate, in previous studies employing patients, the training period, exercise time and intensity were 6–12 weeks, 20–30 min and 50–80% $\dot{V}O_2$peak, respectively, which appears to be shorter or lower compared to untrained healthy subjects. Furthermore, a relative mechanical stimulus to skeletal muscle might be lower in patients than that in untrained healthy adults even if the relative exercise intensity (%$\dot{V}O_2$peak) was the same between both adult groups because exercise intensity was frequently set using $\dot{V}O_2$peak measured by an incremental symptom-limited exercise test. Therefore, a lack of strength gain found after continuous cycle training for the patients may be related to a lower exercise intensity, shorter training period and shorter exercise time compared to the studies employing untrained healthy adults.

Possible mechanisms for cycling-induced muscle hypertrophy

In this section, we discuss the possible mechanisms for continuous cycling-induced muscle hypertrophy due to the insufficient data regarding interval cycling. The following mechanisms may be common to interval cycling because cycling training can induce muscle hypertrophy regardless of exercise type as mentioned previously. However, it should be acknowledged that there may be distinct or subtle differences between continuous and interval cycle exercise.

Muscle activity during pedaling

Numerous studies have reported muscular activation during pedaling using EMG analysis (19, 54, 76). For example, Ericson et al. (19) have quantified the activation of thigh muscles during ergometer cycling as recorded by EMG in recreationally-active students. Peak muscular activation (normalized by EMG recorded during MVC (%MVC)), when performing cycle exercise at 120 W and 60 rpm, was the following values for each muscle: 12% in RF, 54% in VM, 50% in VL, 12% in BF and 10% in medial hamstring (SM and ST). VM and VL muscles were especially activated by cycling exercise and corresponded to ~50% MVC. Meanwhile, Marsh and Martin (54) found that the average %MVC during cycling was approximately 30% in VL at 200 W and 110 rpm in young non-cyclists. In recent years, it has been established that a very low exercise intensity such as 30% 1RM can lead to an increase in myofibrillar protein synthesis when performed repetitively or until volitional failure (9). Therefore, cycle training that consists of repetitive movements may suffice as a minimum stimulus required to increase muscle fiber activation high enough to result in favorable physiologic increases in muscle protein synthesis.

Muscle cell swelling

It is empirically known that a bout of high-intensity cycle exercise induces a temporary increase in thigh size similar to resistance training, which is likely due to a fluid shift from the plasma into the muscle cell. According to hypothetical model for cell swelling introduced by Haussinger (30), cell swelling may affect protein metabolism, gene expression and proteolysis through the activation of MAPK (49). These acute changes in muscle size are considered an indirect measure of muscle cell swelling although the possibility of the increase in muscle size induced by just an increase in interstitial fluid cannot be completely ruled out (49). Ploutz-Snyder et al. (70) have shown that the CSA of vasti and adductor muscle groups increased 10% and 5%, respectively, whereas plasma volume decreased immediately after squat exercise and the reduction of plasma volume was correlated with the increase in muscle CSA. We have confirmed that muscle thickness significantly increased 8% in RF and VL after a bout of 5 min pedaling exercise at 90% VO_2max (unpublished data), the value of which is not largely different from that after a bout of resistance training. Therefore, muscle cell swelling may be one of factors affecting muscle protein metabolism after a bout of cycle exercise.

Muscle protein synthesis (mTOR and MAPK signaling pathway)

Skeletal muscle hypertrophy results from a prolonged shift of muscle protein turn-over towards synthesis rather than breakdown (75). The translation of messenger ribonucleic acid (mRNA) plays a prominent role in protein synthesis following an exposure to exercise stimuli (43, 61). In translation, the mechanistic target of rapamycin (mTOR) enhances mRNA translation through the phosphorylation of eukaryotic translation initiation factor 4E binding protein 1 (4E-BP1) and ribosomal protein S6 kinase 1(S6K1) (8, 9, 16, 17), which in turn results in an increase in muscle protein synthesis. Several mitogen-activated protein kinase (MAPK) signaling pathways such as extracellular signal-regulated kinase (ERK) and p38-MAPK signaling pathways also play an important role in muscle protein synthesis (16, 53). Some studies have shown that a bout of cycle exercise activated both mTOR (55) and MAPK (87) signaling pathway as well as muscle protein synthesis (28). However, the magnitude of increase appears to be smaller for cycle exercise compared to resistance exercise. For example, S6K1 phosphorylation increased above basal values immediately after both cycle and resistance exercise (88). However, after 4 hours, S6K1 phosphorylation remained above basal values only for the resistance exercise (88). Furthermore, one study has shown that myofibrillar protein synthesis was stimulated over the 4-hour period following resistance exercise but not after cycle exercise (88). These results suggest that increased myofibrillar protein synthesis rate after cycle exercise is smaller or slower compared to resistance exercise, or that cycle exercise may not necessarily stimulate myofibrillar protein synthesis. A smaller or slower increase in myofibrillar protein synthesis may provide some explanation for why many training sessions are required for cycle training to induce muscle hypertrophy as mentioned earlier.

Proteolytic gene expression

In addition to protein synthesis, it is known that three proteolytic systems are involved in muscle protein degradation: ubiquitin-proteasome system (UPS), cytosolic calcium-dependent calpain system and the lysosomal system. Among these systems, UPS plays a prominent role in muscle protein breakdown (3, 38) through the elevated expressions of muscle-specific ubiquitin ligases: Atrogin-1 and muscle ring finger 1 (MuRF1) (6, 26). Therefore, it appears that a reduced expression following exercise results in muscle hypertrophy through a positive change in muscle net protein balance (90). Konopka et al. (27, 44) have shown that 12-week cycle training induced muscle hypertrophy and significantly reduced mRNA expression of Forkhead transcription factor 3A (FOXO3A) at rest with a trend for its downstream targets, Atrogin-1 and MuRF1, to also be reduced. Furthermore, FOXO3A significantly decreased 6 hours after an acute bout of 60-minute cycle exercise compared to rest (28). Therefore, following a bout of cycle exercise, the reduction of proteolytic mRNA expression may be another factor contributing to muscle hypertrophy. However, to better determine the overall contribution of reduced proteolytic systems to muscle hypertrophy, more research investigating the change in muscle protein degradation rate following cycle exercise is needed.

Satellite cell

The proliferation of satellite cells may also contribute substantially to muscle hypertrophy (40, 68). Although muscle fibers have multiple myonuclei, the addition of new myonuclei are thought to be important for substantial long term increases in human skeletal muscle mass (31). Satellite cells are ordinarily in a quiescent state but they can increase muscle fiber area through differentiation and ultimate fusion with a muscle fiber if they are activated to enter the cell proliferation cycle when a muscle is injured or subjected to mechanical stress (31). Charifi et al. (13) and Verney et al. (85) have investigated the effect of cycle training on muscle size and satellite cells in older men. They demonstrated that cycle training induced a 12–23% increase in type II a fiber area of VL muscle and increased the number of satellite cells per fiber. However, the number of myonuclei per fiber did not change in either study (13, 85). This is likely because new myonuclei are not required when the magnitude of muscle fiber hypertrophy does not exceed 26% (40) or a myonuclear domain of ~2000 μm^2 (68). Therefore, it is likely that levels of muscle hypertrophy induced by cycle training can be observed independent of changes in myonuclei.

Conclusion

Cycle training appears to be capable of inducing muscle hypertrophy as well as increased aerobic capacity. However, it is plausible that cycle training requires a longer training period than typical resistance training until an increase in muscle size can be observed due to a much slower hypertrophy rate.

Practical applications

Our research suggests that cycle training elicits muscle hypertrophy of the thigh similarly between healthy untrained young and older adults, while strength gain seems to favor older adults. Thus, this suggests that improving muscle quality may be higher in older adults than in young adults. Cycle training is a training mode to produce muscle hypertrophy and strength gain but may not be the most effective way. Cycle training appears to require a relatively longer period of time to promote significant increases in muscle size compared to traditional resistance training. Therefore, trainers and therapists need to select the most suitable training method based on the preference and purpose of exercise training of their clients. Furthermore, future research is needed to determine an optimal training design to maximize the hypertrophic effect and/or strength gain.

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