Peripheral Vascular Changes After Electrically Stimulated Cycle Training in People With Spinal Cord Injury

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ABSTRACT. Gerrits HL, de Haan A, Sargeant AJ, van Langen H, Hopman MT. Peripheral vascular changes after electrically stimulated cycle training in people with spinal cord injury. *Arch Phys Med Rehabil* 2001;82:832-9.

Objective: To test whether a short period of training leads to adaptations in the cross-sectional area of large conduit arteries and improved blood flow to the paralyzed legs of individuals with spinal cord injury (SCI).

Design: Before-after trial.

Setting: Rehabilitation center, academic medical center.

Participants: Nine men with spinal cord lesions.

Intervention: Six weeks of cycling using a functional electrically stimulated leg cycle ergometer (FES-LCE).

Main Outcome Measures: Longitudinal images and simultaneous velocity spectra were measured in the common carotid (CA) and femoral (FA) arteries using quantitative duplex Doppler ultrasound examination. Arterial diameters, peak systolic inflow volumes (PSIVs), mean inflow volumes (MIVs), and a velocity index (VI), representing the peripheral resistance, were obtained at rest. PSIVs and VI were obtained during 3 minutes of hyperemia following 20 minutes of FA occlusion.

Results: Training resulted in significant increases in diameter ($p < .01$), PSIVs ($p < .01$), and MIVs ($p < .05$), and reduced VI ($p < .01$) of the FA, whereas values in the CA remained unchanged. Postocclusive hyperemic responses were augmented, indicated by significantly higher PSIVs ($p < .01$) and a trend toward lower VI.

Conclusion: Six weeks of FES-LCE training increased the cross-sectional area of large conduit arteries and improved blood flow to the paralyzed legs of individuals with SCI.

Key Words: Arteries; Blood flow velocity; Ergometry; Paraplegia; Rehabilitation.

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DRAMATIC ADAPTATIONS occur in a person's central and peripheral circulatory system after a spinal cord injury (SCI). Depending on the severity and level of the lesion, SCI

results in cardiac deconditioning and vasomotor dysregulation.^{1,2} In addition, studies have shown structural and functional adaptations in the peripheral vascular system of the paralyzed limbs. This was indicated by a reduced diameter of the common femoral artery,^{3,4} reduced capillarization,⁵⁻⁷ and a diminished blood flow to the legs,^{3,4,8} all of which probably reflect adaptations to reduced activity and associated decreased metabolic (oxygen) demand. Impaired blood flow, accompanied by decreased oxidative capacity of these predominantly fast twitch muscles,^{9,10} may contribute to early fatigue during electrically stimulated muscle contractions.¹¹

Circulatory properties can adapt to increased muscle activity after voluntary exercise,¹² or as a result of electric stimulation in animals¹³⁻¹⁶ and in humans with SCI.^{5,6} Furthermore, impaired blood flow to the paralyzed limbs of people with SCI can be reversed by electrically stimulated ambulation¹⁷ or standing.⁸ Functional electrically stimulated leg cycle ergometer (FES-LCE) exercise, which is another application of electric stimulation designed to improve health and cardiovascular fitness in people with SCI,¹⁸ may also have beneficial effects on lower limb circulation.

Various studies have assessed the training effects of this exercise mode and reported improved cardiopulmonary fitness,¹⁹ enlarged muscle mass,^{7,20,21} and fiber-type conversion toward more oxidative muscle fibers.^{21,22} These adaptations may all contribute to the improved endurance capacity and power output seen during cycling.^{19-21,23-25} Few studies, however, have investigated peripheral circulatory adaptations after FES-LCE training. Chilibeck et al⁷ showed a proportional increase in capillary number in muscles biopsies obtained from the human paralyzed vastus lateralis muscle after FES-LCE training. To our knowledge, only 1 study⁴ has assessed structural vascular adjustments as well as adaptations in blood flow in the legs of people with SCI after FES-LCE training. Using echo-Doppler ultrasound, which is a noninvasive technique to assess vascular properties, it was shown that individuals with tetraplegia who had participated in FES-LCE training programs for 7 years or less had significantly larger diameters, larger resting arterial blood inflow, and augmented hyperemic responses to occlusion of the femoral artery (FA), compared with sedentary individuals with tetraplegia. The results of this cross-sectional study clearly indicate that prolonged periods of FES-LCE can enlarge the capacity of the vascular system, as well as improve blood flow and reverse the deterioration of lower limb circulation in people with SCI. A longitudinal training study would, however, be desirable to show direct effects of FES-LCE on the circulatory properties of the exercised lower limbs.

Metabolic adaptations that increase the activity of aerobic enzymes and changes in capillary blood flow occur within days or weeks after the start of electric stimulation programs.²⁶ Furthermore, increased capillarization was observed after only 8 weeks of FES-LCE training.⁷ It may be hypothesized that a relatively short period of FES-LCE training will lead to adaptations in the cross-sectional area of large conduit arteries, as well as improved blood flow to the paralyzed lower limbs of

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individuals with SCI. The purpose of this study was, therefore, to assess the effects of a 6-week FES-LCE training program on the structure and function of the lower limb arterial circulation in individuals with SCI.

METHODS

Subjects

The study included 9 men with thoracic and cervical spinal lesions. Table 1 lists the subjects' characteristics with respect to the lesion level and body composition. All subjects participated in a pretraining screening that included a general physical examination by the rehabilitation physician. Joint range of motion, spinal reflexes, and spasticity were evaluated by a local physiotherapist. Subjects with any of the following were excluded: cardiac arrhythmia; high blood pressure (systolic blood pressure, >180mmHg; diastolic blood pressure, >110mmHg); a pacemaker; pressure ulcers; metal implants in the area of stimulation; severely reduced mobility in hip or knee joints; absence of spinal reflexes; and previous bone fractures. All subjects were informed about training and testing procedures and involved risks, after which they gave written informed consent. The Medical Ethical Committee of the University of Nijmegen, Nijmegen, the Netherlands, approved the study.

FES-LCE Training

The cycle training used a computer-controlled leg cycle ergometer.^a This device provides electric stimulation to self-adhesive 50 × 89mm surface electrodes,^b placed over hamstring, gluteal, and quadriceps muscles.

Electric stimulation (duration monophasic square wave pulses, 450μs, 30Hz) was applied in a coordinated sequence allowing cyclic patterns of muscle contractions resulting in leg cycling. The device was programmed to increase the stimulation current, with a maximum of 140mA, to achieve a target pedaling rate of 50rpm. The external pedal resistance of the ergometer could be varied with 1/8kp increments (corresponding with ~6.1W at 50rpm). When the pedaling rate dropped below 45rpm, the resistance was reduced, and when the pedaling rate dropped below 35rpm, the stimulation was terminated.

Training Protocol

All subjects trained for 6 weeks, 3 times a week. A training session consisted of a 30-minute FES-LCE exercise. Each

session started with a 1-minute passive warm-up (without stimulation) as a research assistant turned the crankshaft manually. After the warm-up, stimulation of the leg muscles was started, allowing active FES-LCE training until the subject could no longer maintain the pedaling rate above 35rpm (represents 1 run). When fatigue occurred before the end of the session, the first run was followed by a 5-minute rest period. The procedure was repeated, with a maximum of 5 runs available to complete 30 minutes of active cycling. Each bout of exercise was followed by a 2-minute passive cooling down, during which the assistant turned the pedals. When a subject was able to complete 30 minutes of FES-LCE exercise in 1 run with at least 90% of the programmed pedal resistance, the resistance was increased with 1/8kp in the next training session, up to a maximum of 7/8kp.

Measurements of the Arterial Circulation

Resting arterial diameters, red blood cell velocities of the right common carotid artery (CA) and the right common FA, and hyperemic responses to occlusion of the FA were performed before and after 6 weeks of FES-LCE training. Measurements were taken in a semidark room with subjects in a supine position; a rest period of 5 minutes was included before the tests. Resting systolic blood pressures and resting heart rates were obtained manually with a sphygmomanometer. Resting longitudinal images and simultaneous Doppler spectra were obtained from CA and FA using a 5MHz pulse wave, color coded duplex Doppler ultrasound apparatus.^c For the CA measurements, the probe was placed on the common CA, about 1.5cm proximal to the bifurcation. For the FA measurements, the probe was placed on the common FA, just below the inguinal ligament, about 2cm proximal to the bifurcation. For diameter measurements, images were frozen at the mid and end systolic phase. Three consecutive measurements of resting CA and FA images and Doppler spectra were obtained and recorded on videotape for offline analysis.

Hyperemic responses were induced using a slightly modified tourniquet application. A large cuff was placed around the upper thigh, approximately 5 to 10cm distally from the greater trochanter. The cuff was inflated to 50mmHg above systolic pressure, and this pressure was maintained for 20 minutes. In nonimpaired individuals, the duration of occlusion is usually limited to 5 minutes to obtain maximal hyperemic responses. However, during pilot experiments (unpublished data), we found greater hyperemic responses after longer periods of occlusion in people with SCI. Arresting lower limb circulation for 20 minutes provoked a maximal hyperemic response in these individuals. Although care should be taken regarding possible effects of reperfusion injury after occlusive challenge, a study²⁸ showing such possible injury used much longer periods of ischemia than we did in this study. After the thigh compression was removed, Doppler spectra were recorded continuously for 3 minutes.

Analysis of Variables

One investigator analyzed offline recordings of arterial images and red blood cell velocities. Resting diameters were measured from 3 consecutive images and then averaged. Furthermore, from the corresponding Doppler spectrum waveforms (fig 1), the following blood velocities were determined and averaged for each velocity: (1) peak systolic blood velocity (Vmax), defined as the highest velocity measured in the Doppler spectrum of a cardiac cycle; (2) minimal velocity (Vmin), defined as the lowest velocity in the Doppler spectrum of a cardiac cycle; (3) end-diastolic velocity (Vdia), defined as the velocity at the end of the diastolic phase of a cardiac cycle

Table 1: Subjects' Characteristics With Respect to Body Composition and the Level, Classification, and Duration of the Lesion

Subject	Age (yr)	Height (m)	Weight (kg)	Lesion Level	ASIA Class*	Lesion Duration (yr)
1	44	1.91	95	C5-6	B	14
2	36	1.72	62	C5	A	18
3	30	1.78	68	T4	A	2
4	61	1.80	82	T7-8	A	2
5	40	1.78	78	T8	A	5
6	44	1.85	88	C5	B	27
7	28	1.89	72	T4	A	1
8	44	1.82	87	T7	B	22
9	26	1.83	62	C4-5	C	9

* American Spinal Injury Association²⁷ (ASIA) score is used to classify the completeness of the lesion: A, sensory and motor complete; B, sensory incomplete but motor complete; C, sensory and motor incomplete but no functional motor activity.

Fig 1. Example of resting Doppler spectral waveforms, obtained from (A) the CA and (B) the FA. Vmax is defined as the highest velocity, Vmin as the lowest velocity, and Vdia as the velocity at the end of the diastolic phase of the enveloping Doppler spectrum during the entire cardiac cycle.

(note that in the CA, Vdia was equal to Vmin, because the Doppler spectrum in these arteries demonstrated no reverse flow; fig 1); and (4) mean blood velocity (Vmean), defined as the average velocity of the enveloping Doppler spectrum during the entire cardiac cycle.

Peak systolic inflow volume (PSIV) and mean inflow volume (MIV) were calculated from the product of the arterial cross-sectional area and $\frac{1}{2}V_{\max}$ or $\frac{1}{2}V_{\text{mean}}$, respectively, assuming a parabolic blood velocity profile.

In vessels with such parabolic flow (sometimes referred to as Poiseuille flow), the maximum velocity in the center of the vessel is twice the mean velocity in the entire vessel. A velocity index (VI) was calculated from the difference between Vmax and Vmin divided by Vmax and was used as an indicator for the peripheral resistance. This VI was a slight modification of the Pulsatility Index²⁹ and was independent of possible differences in the insonation angle of the Doppler probe during the recordings. During the first minute of the hyperemic response after occlusion (after the cuff was removed), Vmax and Vmin were determined every 10 seconds. In the following 3 minutes, values were obtained every 30 seconds. In addition, VI and PSIV were calculated from these values, as described previously.

Statistical Analysis

Paired *t* tests were used to compare variables for vascular properties of the FA and CA (arterial diameter, red blood cell velocities, inflow volumes, peripheral resistance) and thigh circumference before and after training. A 2-way analysis of variance for repeated measures was used to test for main effects of training, sample time (including resting values), and their interaction on inflow volumes and peripheral resistance during

the hyperemic response after occlusion. If significant main effects were observed for sample time or the interaction of training and sample time, Tukey post hoc tests were performed. All values are described as mean $\pm$ standard deviation (SD), unless otherwise stated, and levels of significance were set at .05.

RESULTS

FES-LCE Exercise Performance

All 9 subjects completed the 18 training sessions. Their exercise performance improved after the training period, as indicated by an increase in work output from 4 ± 5 kJ, averaged over the first 3 training sessions, to 16 ± 14 kJ, averaged over the last 3 training sessions ($p < .01$).

Resting Vascular Properties

Heart rate and systolic blood pressure were similar after training (68 ± 14 beats/m, 137 ± 7 mmHg, respectively) compared with values before training (65 ± 17 beats/m, 131 ± 20 mmHg). Figure 2 shows the changes in resting diameters, inflow volumes, and peripheral resistance of the CA and FA before and after training. Six weeks of FES-LCE training resulted in a significant increase in diameter of the FA (pretraining, 7.5 ± 1.5 mm vs posttraining, 8.1 ± 1.5 mm, $p < .01$), whereas the diameter of the CA remained unchanged (pretraining, 7.1 ± 0.8 mm vs posttraining, 6.9 ± 0.6 mm). Resting blood cell velocities remained unchanged after training in both FA and CA (table 2). However, VI, which is used as an indicator for peripheral resistance, decreased significantly from 1.24 ± 0.11 to 1.14 ± 0.12 in the FA ($p < .01$), but was unchanged in the CA (pretraining, $.73 \pm .07$ vs posttraining,

Fig 2. Resting vascular properties of the FA and the CA pre- and posttraining. (A) diameter; (B) VI; (C) PSIV; and (D) MIV. Values are means $\pm$ SDs and represent a percentage change after training. * Denotes a significant change posttraining at $p < .01$.

$.74 \pm .06$). In addition, significantly larger resting inflow volumes of the FA were found after training. This was represented by an increase in PSIV from 1330 ± 550 mL/min to 1710 ± 490 mL/min ($p < .01$) and an increase in MIV from 270 ± 120 mL/min to 370 ± 160 mL/min ($p < .05$).

In contrast, no changes in PSIV or MIV were observed in the CA (pretraining PSIV, 1270 ± 390 mL/min vs posttraining PSIV, 230 ± 320 mL/min; pretraining MIV, 540 ± 130 mL/min vs posttraining MIV, 530 ± 130 mL/min).

Hyperemic Response to Occlusion

Figure 3 shows the changes in inflow volumes and peripheral resistance as a result of the release of arterial occlusion of the thigh before and after training. Significant main effects of sample time (including resting values) were observed for postocclusion PSIV ($p < .01$) and VI ($p < .01$). Before training, PSIV was significantly different from resting values at 30 and

40 seconds postocclusion. After training, however, PSIV values were significantly different from resting values starting at 10 seconds until 90 seconds postocclusion. Pretraining and posttraining values for VI were significantly different from resting values throughout the 3 minutes after release of the cuff (except for pretraining at 180s).

After training, the hyperemic response is augmented, as indicated by a significant main effect of training ($p < .01$). PSIV values were significantly higher at rest as well as at all sample times from 10 seconds to 60 seconds. The interaction effect between sample time and training for PSIV during the hyperemic response approached statistical significance ($p = .056$). Furthermore, during postocclusive hyperemia, VI seemed to be slightly lower after training, but no statistical significant main effect of training was observed. There was also no interaction effect between sample time and training for VI.

DISCUSSION

This study investigated structural and functional adaptations of the peripheral circulation of the legs of individuals with SCI after 6 weeks of FES-LCE training. Its main findings were that FES-LCE training resulted in structural adaptations of the conduit arteries, with larger resting diameters of the FA. Furthermore, resting PSIV and MIV increased, indicating higher blood inflow volumes, and VI decreased after training, indicating a reduction in the peripheral resistance. Finally, training augmented the reactive hyperemic response with higher PSIV and a tendency for lower VI after the release of arterial occlusion.

Vascular Properties Before FES-LCE Training

The average CA diameters of individuals with SCI in the present study (7.1mm) are comparable to those previously reported in nonimpaired people (between ~ 6 and ~ 7 mm).³⁰⁻³² However, the average FA diameters of these untrained subjects with SCI (7.5mm) were below values of nonimpaired people, which range between approximately 8 and approximately

Table 2: Resting Red Blood Cell Velocities Obtained From the Common FA and Common CA Before and After 6 Weeks of FES-LCE Training

		Pretraining	Posttraining
Vmax (m/s)	FA	.99 $\pm$.23	1.12 $\pm$.24
	CA	1.03 $\pm$.19	1.12 $\pm$.24
Vmin (m/s)	FA	-.22 $\pm$.09	-.15 $\pm$.12
	CA	.27 $\pm$.04	.28 $\pm$.05
Vdia (m/s)	FA	.13 $\pm$.05	.11 $\pm$.03
	CA	.27 $\pm$.04	.28 $\pm$.05
Vmean (m/s)	FA	.21 $\pm$.09	.24 $\pm$.06
	CA	.44 $\pm$.04	.47 $\pm$.06

NOTE. Vmax represents the highest velocity; Vmin, the lowest velocity; Vdia, the velocity at the end of the diastolic phase; and Vmean, the average velocity of the enveloping Doppler spectrum during the entire cardiac cycle. Values are means $\pm$ SD. No significant differences were found between red blood cell velocities before and after training.

Fig 3. Postocclusive hyperemic response pre- and post-training. (A) PSIV; and (B) VI. Values are means $\pm$ SDs. Significant main effects of sample time were found for both PSIV and VI ($p < .01$). * Denotes significant difference from rest at $p < .01$. † Denotes significant difference from rest at $p < .05$. Significant main effects for training were found for PSIV ($p < .01$), but not for VI. ‡ Denotes significant difference between pre- and posttraining values at $p < .01$.

10mm.^{3,4,30,32-34} This atrophy of the peripheral vascular bed is confirmed by recent studies that reported smaller FA areas,^{3,4} or reduced capillary supply⁵⁻⁷ in people with SCI, compared with nonimpaired controls. Consistent with the reduced FA diameter, FA blood flow in our SCI subjects (270mL/min) also seems reduced when compared with values reported in nonimpaired people (between ~ 300 and ~ 400 mL/min).^{30,33-35} However, flow measured in the CA (540mL/min) lies within the range of values from nonimpaired persons (between ~ 400 and ~ 600 mL/min).^{30,31,36}

This reduced blood flow confirms previous reports of lower FA inflow volumes, obtained with echo-Doppler ultrasound,^{3,4} and lower thigh blood flow, obtained from impedance plethysmography,⁸ in individuals with SCI. Thus, we may conclude that SCI leads to atrophy of the vascular area and reduces blood flow to the paralyzed lower limbs, which probably represents

adaptations to a lower oxygen demand as a consequence of reduced activity of paralyzed muscles.

When comparisons are made between studies, differences in the magnitude of structural as well as functional adaptations might be related to differences in methodology. It is, for example, known that the distension of the arterial diameter during a cardiac cycle is approximately 5% for the CA and 2% for the FA,³⁷ resulting in approximately 10% and 4% variation in arterial flow, respectively. Thus, differences in the phases of the cardiac cycle taken to define arterial diameter may account in part for differences in values between studies. In addition, diversity of values for area and flow may be related to characteristics of the population studied. Hopman et al³ reported even lower values for FA diameter (5.5mm) and flow (192mL/min) in persons with SCI than the values found in our study. In contrast with the study by Hopman,³ however, our study in-

cluded only subjects with intact spinal reflexes that are required for the application of electric stimulation programs. Consequently, it may be speculated that deterioration of the peripheral circulation of the paralyzed limbs in these subjects is limited due to occasional muscle spasms.

Care should be taken when absolute values for structural and functional vascular properties from different studies are compared. However, this study was primarily designed to assess changes in the vascular properties as a result of increased activity induced by FES-LCE. Because in this study design subjects served as their own controls, and the intraobserver variability of duplex ultrasound measurements of lower limb blood flow is relatively low compared with the interobserver variability,³⁸ this technique is useful for studying training effects on vascular properties.

Effect of FES-LCE Training

Our results clearly show that vascular atrophy and reduced lower limb blood flow resulting from reduced activity can be partly reversed after only 6 weeks of FES-LCE training. The increased FA diameter, increased blood inflow volume, and reduced peripheral resistance at rest, as well as the increased responsiveness during hyperemia, are likely to increase the total vascular capacity. Blood flow is the quotient of pressure and resistance. Blood pressure remained unchanged in subjects in this study. Therefore, the consistent decreased peripheral resistance at rest and the trend toward lower peripheral resistance during hyperemia indicate that the higher blood inflow volumes, seen following FES-LCE training, are solely attributable to peripheral vascular adaptations. The increase in FA diameter after 6 weeks of FES-LCE training that we found seems rather small (8%). If we assume the shape of the artery to be circular, however, an 8% increase in diameter would translate to an increase of cross-sectional area approximating 17%.

These findings of structural adaptations, as well as the altered responsiveness of the vascular system after this relatively short exercise period, correspond with results of studies^{4,8,17} that used much longer periods of electric stimulation-induced exercise in individuals with SCI. The enlargement of cross-sectional area, as well as the approximately 40% increase in resting arterial inflow of this study, were only slightly lower compared with other reports.^{4,8,17} Using impedance plethysmography, it was found that thigh blood flow doubled after 3 months of quadriceps strengthening in individuals with SCI training for a functional electric stimulation standing system.⁸ Furthermore, using similar echo-Doppler ultrasound methods, as in the present study, 12 weeks of electrically stimulated standing resulted in an approximately 30% larger FA cross-sectional area and an approximately 55% greater resting arterial inflow volumes.¹⁷ Differences of similar magnitude were found between subjects with SCI participating in a long-term FES-LCE training program (up to 7yr) and their sedentary controls (~30% larger cross-sectional areas and ~50% greater resting flow in FA).⁴ Clearly, vascular properties of the paralyzed legs of people with SCI can change soon after the start of FES-LCE training. These early adaptations correspond with the capillary proliferation, found after only 8 weeks of FES-LCE training,⁷ and are consistent with changes in metabolic profile, which are known to occur within weeks after the start of electric stimulation-induced exercise.²⁶ Furthermore, these exercise-induced adaptations may be responsible in part for the substantial increase in exercise performance reported in this study. Besides an increase in the oxidative capacity of the exercised muscles, which is likely to occur and has been previously reported after chronic electric stimulation of para-

lyzed muscles,^{5,6,21} an improved blood flow to the muscles would enhance the oxygen delivery and removal of metabolic products.

The vascular adaptations after electrically stimulated exercise found in people with SCI resemble the effects of physical exercise on circulatory properties in nonparalyzed humans.^{32,39-41} A recent review⁴² reported that, although a period of exercise training increases the exercise or occlusion-induced hyperemic responses in nonimpaired individuals, this normally does not affect resting blood flow. It may, therefore, be surprising that the present study, in contrast with the findings in nonimpaired individuals, showed higher inflow volumes and lower peripheral resistance after training at rest. However, the impact of exercise training on paralyzed muscles in people with SCI is expected to be much greater than in nonimpaired people. The dramatic deterioration of circulatory properties after long-standing inactivity permits greater adaptation after exercise training. Furthermore, the amount of exercise-induced activity in proportion to total activity is much greater in people with SCI than in nonimpaired persons. Apart from occasional muscle spasms, the muscles of SCI individuals are activated only during training, whereas muscles of the nonimpaired are continuously activated during daily activities. Finally, the neural sympathetic pathways are interrupted after SCI. Normally, blood flow at rest is determined by the inherent myogenic activity of the resistance vessels and a relatively high sympathetic nerve activity.⁴³ Although it is not clear how SCI affects vascular control, it may be expected that the sympathetic tone on the resistance vessels would be reduced, which is known to increase peripheral blood flow.⁴³ Therefore, it may be speculated that resting blood flow would more closely reflect the capacity of the vascular bed. Furthermore, an enlarged vascular capacity, induced by training of the paralyzed muscles, would inevitably lead to increased resting blood flow.

Structural vascular adaptation, such as vascular growth, remodeling, or angiogenesis, can occur as a consequence of an imbalance between metabolic requirement and supply. Local hypoxia, for example, induces diameter growth of major arteries in chicken embryos⁴⁴ and is also believed to be an important factor for capillary proliferation.⁴⁵ In addition, mechanical factors, such as increased wall tension or shear stress as a result of increased blood flow, may also induce vascular growth.¹⁴ It is likely that both metabolic imbalance and mechanical stress on the blood vessels are induced by FES-LCE training, which may underlie the vascular adaptations found in this study. Although we did not measure capillarization, proportional increases in the capillary supply of the exercise-trained vastus lateralis muscles of individuals with SCI⁷ have been found after a similar FES-LCE training program, confirming previous effects of electric stimulation on animal muscle¹³⁻¹⁶ and paralyzed human muscle.^{5,6} In addition to structural vascular changes, adaptations in the control of vascular tone by changing the adaptive responsiveness of the vascular endothelium may also be responsible for the results of the present study. Increased flow or wall shear stress, plus chemical factors, such as metabolites liberated during exercise, catecholamines, or other vasoactive substances, are thought to induce endothelial adaptations and affect vascular tone.⁴⁶ Clearly, our study does not provide information about the triggers for the vascular adaptations found in paralyzed limbs after a period of FES-LCE training. Future research that investigates the time course of training effects on vascular adaptations can improve our understanding of the plasticity of vascular system.

CONCLUSION

The results of our study confirm the hypothesis that a relatively short period of FES-LCE training can increase the area of large conduit arteries and improve blood inflow volume to the lower limbs. This increased vascular capacity is primarily attributed to peripheral adjustments, such as vascular growth or altered vascular control to exercise-induced mechanical or metabolic changes, and may be partly responsible for the improved exercise performance seen during FES-LCE training.

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