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ORIGINAL ARTICLE

The effects of exercise training on physical capacity, strength, body composition and functional performance among adults with spinal cord injury: a systematic review

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Study design: Systematic review.
Objectives: To conduct a systematic review of evidence surrounding the effects of exercise on physical fitness in people with spinal cord injury (SCI).
Setting: Canada.
Methods: The review was limited to English-language studies (published prior to March 2010) of people with SCI that evaluated the effects of an exercise intervention on at least one of the four main components of physical fitness (physical capacity, muscular strength, body composition and functional performance). Studies reported at least one of the following outcomes: oxygen uptake/consumption, power output, peak work capacity, muscle strength, body composition, exercise performance or functional performance. A total of 166 studies were identified. After screening, 82 studies (69 chronic SCI; 13 acute SCI) were included in the review. The quality of evidence derived from each study was evaluated using established procedures.
Results: Most studies were of low quality; however, the evidence was consistent that exercise is effective in improving aspects of fitness. There is strong evidence that exercise, performed 2–3 times per week at moderate-to-vigorous intensity, increases physical capacity and muscular strength in the chronic SCI population; the evidence is not strong with respect to the effects of exercise on body composition or functional performance. There were insufficient high-quality studies in the acute SCI population to draw any conclusions.
Conclusions: In the chronic SCI population, there is good evidence that exercise is effective in improving both physical capacity and muscular strength, but insufficient quality evidence to draw meaningful conclusions on its effect on body composition or functional capacity.
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Keywords: exercise; strength training; aerobic training; physical fitness; paraplegia; tetraplegia

Introduction

Although a growing number of studies suggest that exercise can improve physical fitness in people with spinal cord injury (SCI), currently there are no rigorously developed, clinical practice guidelines for prescribing exercise to this population. Without guidelines, exercise prescription and promotion are challenging. High-quality guidelines are developed using systematic methods that combine rigorous methodology with the meaningful engagement of a multidisciplinary team of stakeholders.[1] Methodologically, guidelines begin with a clinical practice question that informs a systematic review of relevant research evidence. In a systematic review, procedures used to identify studies for inclusion are clearly stated and reproducible. An appraisal of the quality of evidence accompanies the evidence synthesis. This evidence base provides the foundation for the guideline team to make recommendations.[1]

Two systematic reviews have examined the effects of exercise on physical fitness, with the intention of providing recommendations for prescribing physical activity to people with SCI. The first[2] aimed at identifying the characteristics of training regimens associated with physical capacity changes. Virtually all of the included studies utilized upper-body training. Although the authors did not formally evaluate study quality, they did report tremendous variability in the training regimens utilized across 25 included studies. Based on their review, they recommended 30 min of rhythmic exercises, 3 days per week at $\geqslant$70% of the maximum heart rate (HR) for 8 weeks, to improve cardiovascular endurance.

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The second systematic review[3] focused on determining the effects of different modes of upper body exercise on physical capacity, reflected by peak oxygen uptake and power output. Methodological quality was evaluated for each of the 25 studies included. The authors concluded that upper-body exercise may increase physical capacity among people with SCI. However, given the overall low quality of evidence, it was impossible to generate evidence-based conclusions regarding the most effective training modes or the relative effects for those with paraplegia versus tetraplegia.

Although these systematic reviews contribute to the evidence base for developing exercise guidelines, they are restricted to one aspect of fitness—physical capacity—and, for the most part, upper-body exercise training programs. No systematic review has examined the effects of all types of exercise training on all four components of physical fitness: physical capacity, muscular strength and endurance, body composition and functional performance. Given the importance of all four fitness components for health, independence and quality of life (QoL),[4] it is important to determine whether exercise can improve each of these in people with SCI.

The present systematic review was undertaken as part of a larger project to develop exercise guidelines for people with SCI. In 2009, a guideline development team of stakeholders was assembled in Canada. A subgroup undertook a systematic review to address the following questions: 'Can exercise improve each fitness component?' and, if so, 'What types of exercise improve each component?' A second objective was to catalog data regarding the effects of different exercise prescriptions on fitness outcomes. Together, this information would provide the evidence base for the team's subsequent deliberations and recommendations in the guideline development process.[5]

Methods

Scope of the review/study inclusion criteria

The review focused on published, English-language studies of the fitness benefits of a physical activity or exercise training intervention in persons diagnosed with an SCI (paraplegia or tetraplegia). Studies had to include at least one of the following fitness measures in the analyses: strength, oxygen uptake/consumption, power output, peak work capacity, body composition, exercise performance or functional performance. Case studies, experimental and quasi-experimental designs were included.

Literature search strategy

Two authors (BF, DLW) conducted searches in the following electronic bibliographical databases:

- MEDLINE (1950–March 2010, OVID Interface);
- PsycINFO (1840– March 2010, Scholars Portal Interface);
- EMBASE (1980–March 2010, OVID Interface);
- CINAHL (1982–March 2010, OVID Interface);
- SPORTDiscus (–March 2010).

Medical Subject Headings included the following search terms (in combination with 'spinal cord injury' OR 'tetraplegia' OR 'paraplegia'): exercise, physical activity, training, exercise conditioning, physical fitness, exercise prescription, adaptation, effect, benefit, strength, aerobic capacity, endurance and body composition.

Screening

Figure 1 shows the flow of articles through the search and screening process. After removing duplicate citations, two authors (BF, KAMG) independently scanned the title and abstract of each citation ($n=3226$) to determine its suitability. Eighty-one articles were retained. Additional articles were identified from references in other review articles ($n=69$) and through hand searches of the authors' personal databases ($n=16$). These 166 articles were read by BF and KAMG (unblinded) to determine whether they met the inclusion criteria. Discussion with a third author (ALH) ensued in cases of disagreement. Full (100%) consensus was achieved for all citations. Eighty-four articles were excluded after review (reasons available from the first author). Eighty-two studies were retained for review, divided into studies involving people with acute SCI (<1 year post injury; $n=13$) and studies involving people with chronic SCI (>1 year post injury; $n=69$).

Data extraction

Two authors (BF and CP) completed data extraction forms for the 82 studies. Extracted data were verified by two additional authors (ALH and KAMG), and included study design, participant characteristics, methodology, outcomes related to our defined scope and conclusions. Reviewers were not blinded to the journal or authors.

Assessment of evidence quality

The quality of each study was determined using the procedures outlined in SCIRE (Spinal Cord Injury Rehabilitation Evidence).[6] Specifically, randomized controlled trials (RCTs) were evaluated using the 10 internal validity items of the Physiotherapy Evidence Database (PEDro) tool. Consistent with the quality-assessment approach used in Valent *et al*.'s review,[3] two items—'blinding of all therapists' and 'blinding of all subjects'—were considered irrelevant when comparing a training group with a no-exercise control group; such studies were credited the two points for these items. The maximum PEDro score is 10. Higher scores reflect better-quality trials. All other studies were evaluated using a modified Downs and Black scale,[7] identical to that used by the SCIRE process, with a maximum score of 28. Higher scores indicate better methodological quality. Articles were independently evaluated by three raters (DLW, BF and CP). Any scoring discrepancies were resolved through discussion. The level of evidence associated with each study was then coded using the SCIRE system, which is a 5-level system that distinguishes between studies of differing quality and incorporates the types of research designs common in SCI rehabilitation research (Table 1).[6]

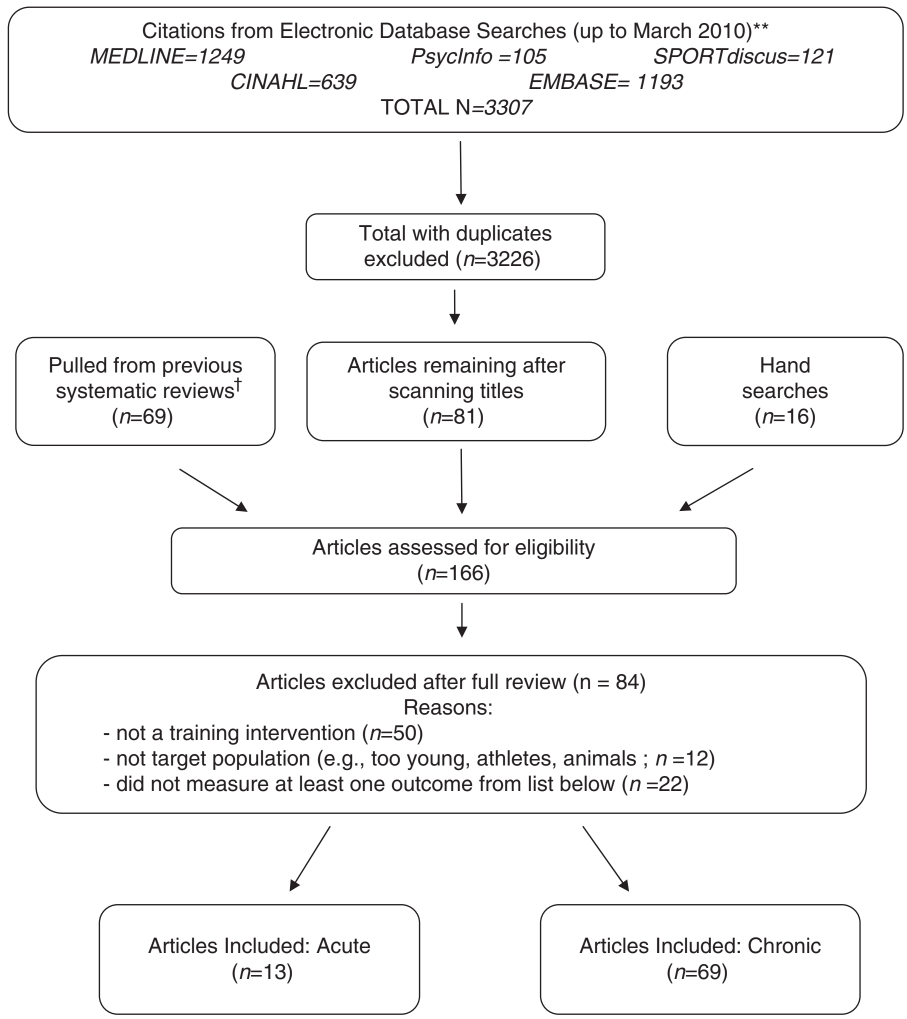

Figure 1 Literature search strategy.

Table 1 The levels of evidence-scaling criteria applied to the articles

Levels of evidence	*Criteria*
Level 1	Randomized controlled trial, PEDro score >6
Level 2	Randomized controlled trial, PEDro score <6 Prospective controlled trial (not randomized)
Level 3	Case–control studies
Level 4	Pre–post, post-test and case series
Level 5	Case report

Results

Extracted data and quality assessment for each study are presented in Tables 2 and 3. Evidence summaries are presented in Tables 4 and 5. Studies of acute (⩽12 months post injury) and chronic patients (>12 months post injury) are summarized separately. These groups have been divided based on accepted knowledge that the greatest degree of functional recovery occurs in the first 12 months following SCI. Owing to the limited evidence base, studies and results have not been divided based on level of injury or completeness of injury.

Studies of acute SCI patients

Physical capacity. Decreased physical capacity is common post SCI and can be attributed to decreased sympathetic drive, muscle atrophy, loss of motor control and relative inactivity.[8,9] Six training studies examined changes in exercise capacity using measures of aerobic capacity and power output.

Aerobic capacity: Increases in peak oxygen consumption (VO_{2peak}) following training is a consistent finding across the level 1 and level 4 studies. One study[10] noted significant increases in VO_{2peak} following 6 weeks of wheelchair interval training 3× per week. Significant increases were also observed following a 6-week arm ergometry training program.[11] Participants training at a high intensity (70–80% HR reserve) showed a significantly greater improvement in VO_{2peak} compared with those training at a low intensity (40–50% HR reserve) over 8 weeks.[12] Injury level seems important in predicting change in VO_{2max}. Hjeltnes *et al.*[13] found participants with paraplegia had a 28% increase in peak oxygen uptake throughout the ~4-month training period, but there was no change in those with tetraplegia.[13]

Table 2 Evidence from acute studies

Reference	n	Lesion range	Age (years), mean ± s.d.	Time since injury, mean ± s.d.	Training program characteristics					Outcomes
					Type	*Intensity*	*Time (min)*	*Frequency*	*Duration*	
Bizzarini *et al.*[16] (D&B = 14)	21	C4–L2	33.8 ± 14.8	92.7 ± 14.8 days	Arm ergometers, wheelchair ergometers, resistance pullies; if AIS C leg press	60–70% max. HR, 12–16 RPE scale; 40–60% 1RM	90	5	6	Training workload: ↑ Anthropometric measures Body weight: ↓ BMI: ↓ Waist/hip ratio: ↓ Sum of 4 skinfolds: ↓ Fat mass: ↓ Fat-free mass: ↓
de Groot *et al.*[12] (PEDro = 7)	6	C5–L1	36 ± 13	116 ± 77 days	Arm ergometry	HI: 70–80% HRR LI: 40–50% HRR	60	3	8	Power output (W) Maximal exercise test: HI: ↑* LI: ↑* Oxygen uptake (VO_2) Maximal exercise test: HI: ↑*^ LI: ↑*
Dobkin *et al.*[47] (PEDro = 7)	117		E1: 31 E2: 23.5	<8 weeks	E1: BWSTT and overground training E2: Standing and overground mobility training	Speed $>0.72\,m\,s^{-1}$	E1: 60 (20–30 BWSTT) E2: 60	5	12	Treadmill walking abilities Speed: E1:↑, E2: ↑ Distance: E1:↑, E2: ↑ Functional performance FIM-L: E1: ↑, E2: ↑ LEMS: E1: ↑, E2: ↑ Berg Balance Scale Score: E1: ↑, E2: ↑ WISCI: E1: ↑, E2: ↑
Dobkin *et al.*[48] (PEDro = 5)	133	C5–L3		4.5 weeks	E1: BWSTT and overground training E2: standing and overground mobility training		60	3–4	12	Treadmill walking abilities Speed: E1:↑, E2: ↑ Distance: E1:↑, E2: ↑ Functional performance FIM-L: E1: ↑, E2: ↑ LEMS: E1: ↑, E2: ↑
Duran *et al.*[14] (D&B = 16)	13	T3–T12	26.3 ± 8.3	25 months	Mixed exercise program (mobility, coordination, strength, aerobic resistance, relaxation)	40–80% max. HR	15–120	3	16	Muscle strength Bench press: ↑* Military press: ↑ * Butterfly press: ↑ * Progressive arm crank test Power output (W): ↑ * Wheelchair skills test (time): ↓* Body weight: ↓ FIM: ↑ *
Gardner *et al.*[19] (D&B = 10)	1	C5/6	28	7 months	BWSTT	32% BWS	20	3	6	Gait variables Gait speed: ↑ * Cadence: ↑ Stride length: ↑ % of right stance: ↓ %Right swing: ↑ %Left stance: ↓ %Left swing: ↑
Giangregorio *et al.*[15] (D&B = 16)	4	C3–C8	29.6 ± 8.7	114.2 ± 47.1 days	BWSTT		5–15-min bouts x 3	2	24–32	BWSTT walking abilities %BWS: ↓ (#) Treadmill speed: ↑ (#) Walking duration per bout: ↑ (#) Lean and fat mass

Table 2 Continued

Reference	n	Lesion range	Age (years), mean ± s.d.	Time since injury, mean ± s.d.	Training program characteristics: Type	Intensity	Time (min)	Frequency	Duration	Outcomes
										Lean mass: ↑ (#) Fat mass: ↑ (#) Mid-thigh muscle CSA: ↑ (#) Lower leg muscle CSA: ↑ (#) Mid-thigh fat CSA: ↑ (#) Lower-leg fat CSA: ↑ (#)
Glinsky *et al.*[49] (PEDro = 9)	31	C4–C7	E: 31 ± 16 C: 47 ± 20	E: 1 years C: 0.4 years	E: dynamic resistance exercise program on the wrist extensor muscles C: no training program	E: 3 sets of 10 repetitions, weight increased if participants could lift weight more than 10 times		3	8	Isometric torque (wrist extensors) E: ↑, C: ↑ Canadian Occupational Performance Measure Performance: E: ↑, C: ↑ ^ Satisfaction: E: ↓, C: ↑ ^
Glinsky *et al.*[50] (PEDro = 7)	32	C4–C7	38 ± 16	5 months	E: NMES-assisted progressive wrist resistance training C: progressive resistance training on the wrist	6 sets of 10 contractions, weight increased if participant could lift weight more than 10 times		3	8	Voluntary wrist extensor strength E: ↑, C: ↑ Voluntary endurance E: ↔, C: ↔ NMES-assisted endurance E: ↑, C:↑
Hjeltnes and Wallberg-Henriksson[13] (D&B = 16)	10	C6–C8	25 ± 2.0	99 ± 6 days	Arm cycling	High intensity	30 min or until exhaustion	3	12–16	Muscle strength score: ↑* Power output Peak exercise test:↑* Submax. exercise test:↔ Oxygen uptake (VO_2) Peak exercise test:↑ Submax. exercise test: ↑ * Body weight: ↔
Le Foll-de Moro *et al.*[10] (D&B = 14)	6	T6–T11/12	29 ± 14	94 ± 23 days	Interval wheelchair ergometry	6 work bouts of 5 min (4 min moderate, 1 min intense)	30	3	6	Power output (W) Maximal exercise test: ↑* Oxygen uptake (VO_2) Maximal exercise test: ↑*
Sutbeyaz *et al.*[11] (D&B = 15)	20	T6–T12	31.3 ± 8.2	3.8 ± 5.8 months	Arm crank ergometry	75% Max. VO_2	15–30	3	6	Power output (W): ↑* Oxygen uptake (VO_2): ↑* Exercise time: ↑*
Tawashy *et al.*[18] (D&B = 11)	1	C5	22	12 weeks	Aerobic exercise: arm ergometry, sliding motion, wheeling	50% HRR at baseline, 70–80% HRR at end	5 min each station, 30 min total	3	10	Power output (W) VO_2 peak test: ↑ Oxygen uptake (VO_2) VO_2 peak test: ↑ 6-MAT: ↓ Exercise performance VO_2 peak test: ↔ 6-MAT: ↔ Timed functional wheeling Flat distance: ↓ Ramp: ↓

Symbols: *, Sig. difference pre–post; ^, sig. difference between groups (i.e., E versus C); #, sig. not indicated.
Abbreviations: AIS, ASIA (American Spinal Injury Association) Impairment scale; BWS, body weight support; BWSTT, body weight-supported treadmill training; D&B, Downs & Black quality assessment tool; FIM-L, functional independence measure—for walking; HI, high intensity; HR, heart rate; HRR, heart rate reserve; LEMS, lower-extremity motor score; LI, low intensity; NMES, neuromuscular electrical stimulation; PEDro, Physiotherapy Evidence Database; 1RM, 1 repetition maximum; RPE, rating of perceived exertion; 6-MAT, 6-minute arm test.

Table 3 Evidence from chronic studies

Reference	n	Lesion range	Age (years), mean ± s.d.	Time since injury (years), mean ± s.d.	Training program characteristics					Outcomes
					Type	*Intensity*	*Time (min)*	*Frequency (times per week)*	*Duration (weeks)*	
Adams *et al.*[51] (D&B = 10)	1	C4	27		BWSTT	59% BWS; 0.5 km h^{-1}	15 (3 × min)	3	12	BWSTT training Walking speed: ↑ (#) Distance per session: ↑ (#) % BWS: ↔ (#) Vastus lateralis CSA Mean: ↑ (#) Type I: ↓ (#) Type IIa: ↑ (#) Type IIx: ↑ (#)
Barstow *et al.*[52] (D&B = 12)	8	C5–T12	34.4 ± 5.6	10.1 ± 4.1	FES cycling	50 r.p.m., increasing work rate	30	3	8	Power output (W) Incremental exercise test: ↑* Oxygen uptake (VO_2) Incremental exercise test: ↑* Constant exercise test: ↓
Belanger *et al.*[53] (D&B = 10)	14	C5–T6	66.4 ± 12.3	9.6 ± 6.6	FES resistance training		60	5	24	Maximal torque: ↑*
Bjerkefors *et al.*[54] (D&B = 12)	20 E:10 C:10	T3–T12	38 ± 12	Median: 11.5	Shoulder-Kayak ergometer training		60	3	10	MVC shoulder Overall strength: ↑* during movement: ↑ Position: ↑*
Bougenot *et al.*[55] (D&B = 11)	7	T6–L5	35.0 ± 13.0	12.3 ± 10	Interval wheelchair ergometer	4 min per bout moderate, 1 min per bout heavy (80% max. HR)	45 (9 × 5 min)	3	6	Power output (W) Maximum wheelchair exercise test: ↑* Oxygen uptake (VO_2) Maximum wheelchair exercise test: ↑*
Cameron *et al.*[56] (D&B = 9)	11	C4–C7	Range: 18–45	>1	NMES cycling	2 mph	20 (4 × 5 min)	3	8	Manual muscle test Biceps: smallest ↑ Triceps: biggest ↑
Carvalho de Abreu *et al.*[57] (D&B = 14)	15 E:8 C:7	C4–C7	31.9 ± 8.0	66.4 ± 48.2 months	E: Treadmill gait training with NMES C: reg. physio.	30–50% BWS; 0.5 km h^{-1}; max. 200 V	20	2	26	Max. gait speed: ↑ Quadriceps CSA MRI: E: ↑*, C: ↓ Gray scale: E: ↑, C:↓
Carvalho de Abreu *et al.*[40] (D&B = 16)	15 E:8 C:7	C4–C7	E: 32.3 ± 3.5 C: 32.8 ± 3.5	E: 64.1 ± 96.2 months C: 55.3 ± 10.6 months	E: Treadmill gait training with NMES C: reg. physio. for 6 months; treadmill gait training w/o NMES for 6 months	30–50% BWS; 0.14 m s^{-1}; max. 200 V	20	2	26	Max. gait speed: ↑ Quadriceps CSA (MRI): E: ↑*, C: ↓
Chilibeck *et al.*[58] (D&B = 14)	6	C5–T8			FES leg ergometry	50 r.p.m.	30	3	8	Power output (W) Training program: ↑* Training program characteristics Continuous pedal (time): ↑* Work output (kJ): ↑* Vastus Lateralis (muscle biopsy) Muscle fiber area: ↑* % II fibers: ↓
Chilibeck *et al.*[59] (D&B = 10)	5	C5–T8	Range: 31–50	Range: 31–50	FES cycling	50 r.p.m.	30	3	8	Power output (W) Training program: ↑* Continuous pedal (time): ↑*

Table 3 Continued

Reference	n	Lesion range	Age (years), mean ± s.d.	Time since injury (years), mean ± s.d.	Training program characteristics					Outcomes
					Type	Intensity	Time (min)	Frequency (times per week)	Duration (weeks)	
Crameri et al.[60] (D&B = 12)	5	C6–T7			Leg FES: Leg 1 (L1): statically with load Leg 2 (L2): dynamically with min. load	L1: 50 ± 6 V L2: 48 ± 7 V; work:rest (min) week 1: 5:5; week 10: 1–15:5	45	3	10	Isometric leg extension force test: L1: ↑* ^, L2: ↑* Vastus lateralis CSA (biopsy) type I fibers: L1: ↑* ^, L2: ↑ Type II fibers (total): L1: ↑* ^, L2: ↑* Type IIa fibers: L1: ↑* L2: ↑* Type IIx fibers: L1: ↓* L2: ↓*
Crameri et al.[61] (D&B = 11)	6	T4–T12	35.5	16.5	FES cycling		30	3	10	Muscle function test: ↑* Muscle biopsy (vastus lateralis) type IIA: ↑* Type IIX: ↓* Type I: ↑ Total CSA: ↑*
de Carvalho et al.[62] (D&B = 17)	21 E:11 C:10	C4–C8	31.9 ± 8.0	66.4 ± 48.2 months	E: Treadmill gait training with NMES C: reg. physio.	30–50% BWS; 0.5 km h^{-1}; max. 200 V	20	2	26	Oxygen uptake (VO_2) Training program E (gait): rest ↓, gait (0.5 km h^{-1}): ↑ C (knee extension): rest: ↑*, knee ext.: ↑* Max. training speed E: ↑
de Carvalho et al.[63] (D&B = 18)	21 E:11 C:10	C4–C8	31.9 ± 8.0	66.4 ± 48.2 months	E: Treadmill gait training with NMES C: reg. physio.	30–50% BWS; 0.5 km h^{-1}; max. 200 V	20	2	26	Oxygen uptake (VO_2) Training program E: rest: ↓, gait: ↑* C: rest: ↑*, knee ext.: ↑*
DiCarlo, 1982[27] (D&B = 6)	1	C6	24	3	Arm ergometry	Target HR: 96 b.p.m.; resistance = 0.5k; 50–60 r.p.m.	5–35	3	8	Oxygen uptake (VO_2) Graded exercise test: ↑ (#) Physical work capacity: ↑ (#) Body weight: ↔ (#)
DiCarlo, 1988[28] (D&B = 9)	8	C5–C7	23.6 ± 4.2	8.5 ± 6.4	Arm ergometry	60–80% Max. HR	5–35	3	8	Oxygen uptake (VO_2) Submax. exercise test: ↑* Distance wheeled: ↑* Physical work capacity: ↑* Body weight: ↓
DiCarlo et al., 1983[23] (D&B = 7)	4	C5–T8	24.3 ± 3.4	11.5 ± 8.5	Arm ergometry	60–80% Max. HR	30	3	5	Oxygen uptake (VO_2) Max. exercise test: ↑* Work load Max. exercise test: ↑
Ditor et al.[64] (D&B = 14)	8	C4–C5	27.6 ± 4.8	9.6 ± 7.5	BWSTT	BWS customized to veach SS; 0.5 km h^{-1} initially	15–60	3	26	Training program measures Speed of ambulation: ↑* Duration of ambulation: ↑
Duffell et al.[20] (D&B = 18)	19 E:9 C:10	T3–T9	E: 41.8 ± 2.3 (s.e.) C: 30.6 ± 3.2 (s.e.)	E: 10.7 ± 2.1 (s.e.)	E: FES cycle training C: AB controls (no training)	45–55 r.p.m.	60	Week 1–8: 3; week 8–16: 4; week 17–57: 5	57	Max. quadriceps torque E: ↑ *, C: ↑* Power output (W) Max. exercise test: E: ↑*

Table 3 Continued

Reference	n	Lesion range	Age (years), mean ± s.d.	Time since injury (years), mean ± s.d.	Training program characteristics					Outcomes
					Type	*Intensity*	*Time (min)*	*Frequency (times per week)*	*Duration (weeks)*	
Duran *et al.*[14] (D&B = 16)	13	T3–T12	26.2 ± 8.4	25.0 ± 34.0	Mixed exercise program	40–80% Max. HR	15–120	3	16	Weight lifted Bench press: ↑* Military press: ↑* Butterfly press: ↑* Exercise performance Max. resistance (arm exercise test): ↑* Wheelchair skills (time): ↓* Body weight: ↑
Effing *et al.*[65] (D&B = 13)	3	C5–C7	51.7 ± 7.0	95.7 ± 89.9 months	BWSTT	Initially 50% BWS	30	5	12	Training parameters Distance walked: ↑ (#) Velocity: ↑ (#) %BWS: ↓ (#) Duration of training session: ↑ (#) ADL performance measures 7 m walking test steps: ↑ 7 m walking test speed: ↑ Get up and go test: ↑
El-Sayed *et al.*[66] (D&B = 10)	12 E: 5 C: 7	Below T10	E: 31.0 ± 2.9 C: 32 ± 1.6		E (SCI) and C (AB): arm ergometer	60–65% VO_{2peak}	30	3	12	Oxygen Uptake (VO_2) Submax. Arm Cranking Exercise E: ↑*, C: ↑*
Faghri *et al.*[67] (D&B = 12)	13	C4–T10	30.5 ± 5	8	FES cycling	50 r.p.m., increasing work rate	30	3	12	Power output (W) Submax. exercise training Quadriplegic: ↑, paraplegic: ↑ Oxygen uptake (VO_2) Submax. exercise training: ↔
Field-Fote *et al.*[68] (D&B = 15)	18		31.7 ± 9.4		BWSTT, with FES and treadmill walking	Customized to SS	90	3	12	Training program measures Treadmill walking speed: ↑* Treadmill walking distance per session: ↑* Overground walking 2 min timed walk—speed: ↑*
Field-Fote *et al.*[46] (PEDro = 6)	27 TM: 7 TS: 7 OG: 7 LR: 6	TM: C3–C6 TS: C5–T5 OG: C3–T4 LR: C4–T10	TM: 40.6 ± 18.4 TS: 40.9 ± 7.8 OG: 48.1 ± 10.0 LR: 43.2 ± 8.4	TM: 7.0 ± 3.1 TS: 8.9 ± 8.1 OG: 3.7 ± 3.5 LR: 8.7 ± 8.4	TM: treadmill with manual assistance TS: treadmill with stimulation OG: overground training with stimulation LR: treadmill with robotic assistance	BWS customized to each SS	60	5	12	Gait measures Short-bout walking: ↑* Long-bout walking: ↑* Training speed: ↑* Step length: TM: ↑, TS: ↑, OG: ↑, LR: ↓ (#), symmetry: ↑ (#)
Forrest *et al.*[32] (D&B = 11)	1	C6	25	1	Locomotor training	Progressive increasing BWS	54.45 ± 13.03	3	39	Overground standing (time): ↑ (#) Body composition Lean body mass: ↑ (#) Fat mass: ↑ (#) Body weight: ↑ (#) Calf diameter: ↑ (#)

Table 3 Continued

Reference	n	Lesion range	Age (years), mean ± s.d.	Time since injury (years), mean ± s.d.	Training program characteristics					Outcomes
					Type	Intensity	Time (min)	Frequency (times per week)	Duration (weeks)	
Fukuoka *et al.*[69] (D&B = 11)	8	T7–L1	46.5 ± 8.3		Wheelchair exercise training	50% HRR	30	3	8	Power output (W) Submax. exercise test: ↑ Oxygen uptake (VO_2) Submax. exercise test: ↓ Maximal exercise test: ↑*
Gass *et al.*[44] (D&B = 12)	7	C5–T4	34.4 ± 11.0	11.71 ± 4.82	Wheelchair training on treadmill	Until exhaustion		5	7	Wheelchair treadmill test (time): ↑* Oxygen uptake (VO_2) Max. wheelchair treadmill test: ↑* Body composition Body weight: ↑ Chest circum: ↑ Waist circum: ↑ Arm circum: ↔ Skinfolds (total): ↓
Giangregorio *et al.*[34] (D&B = 18)	13	C4–T12	28.8 ± 8.1	7.7 ± 6.7	BWSTT	BWS customized to each SS; initial approx 60 BWS at 0.6 km h^{-1}	5–15 min walking bouts, max. 3 bouts per session	3	12 months	Muscle CSA T_{high}: ↑* Calf: ↑* Whole body scan Fat mass: ↑ Lean mass: ↑*
Granat *et al.*[70] (D&B = 15)	6	C3–L1	31.5	7.3	FES gait training		30	5	36	Manual muscle test Hip flexors: ↑* Knee extensors: ↑* Maximal muscle torque Quadriceps: ↑* Training program measures Stride length: ↑* Speed: ↔ Cadence: ↔
Grange *et al.*[71] (D&B = 12)	14 E: 7 C: 7		E: 35.2 ± 15.9 C: 26.6 ± 6.2	12.3 ± 10	E (SCI) and C (AB): square wave exercise tests (SWEET) training	Successive 5-min work bouts: 4 min moderate, 1 min heavy	45	3	6	Power output (W) Max. exercise test: E: ↑*, C: ↑* Oxygen uptake (VO_2) Max. exercise test: E:↑*, C: ↑*
Gregory *et al.*[26] (D&B = 11)	3	C5–T4	47.0 ± 21.70	18.7 ± 2.2 months	Lower body resistance and plyometrics	Resistance: ~70–85% 1RM	30	2–3 (30 sessions)	12	Isometric torque Knee extensors: ↑ (#) Plantar flexors: ↑ (#) 10 m walk Gait speed: ↑ (#) Step length: ↑ (#) Cadence (steps min^{-1}): ↑ (#) Muscle CSA (MRI) Hamstring: ↑ Knee extensors: ↑ Plantar flexors: ↑
Gurney *et al.*[72] (D&B = 12)	6	C4–T4	30.2	10.7	FES cycling and hybrid exercise	50 r.p.m.		3	6 FES cycling, 6 hybrid exercises	Oxygen uptake (VO_2) Incremental exercise test: ↑*

Table 3 Continued

Reference	n	Lesion range	Age (years), mean ± s.d.	Time since injury (years), mean ± s.d.	Training program characteristics					Outcomes
					Type	Intensity	Time (min)	Frequency (times per week)	Duration (weeks)	
Heesterbeek *et al.*[24] (D&B = 16)	10	T2–T12	39.3 ± 8.7	10.5 ± 6.4	Hybrid FES cycling	60–70% VO_2 max.	40	4	8–12	Power output (W) Graded hybrid exercise test: ↑* Leg power during stimulation: ↑ Oxygen uptake (VO_2) Max. graded exercise test: ↑*
Hicks *et al.*[73] (D&B = 18)	13	C4–T12/L1	28.9	7.4 ± 6.9	BWSTT	60% BWS, 0.6 km h^{-1} at start	3 bouts per session, gradual increase in time	3	12 months	Training program measures % BWS: ↓* Speed: ↑* Distance: ↑*
Hicks *et al.*[22] (PEDro = 7)	23 E:11 C:12	C4–L1	E: 36.9 ± 11.4 C: 43.2 ± 9.3	E:7.7 ± 6.4 C:12.1 ± 7.3	E: Arm ergometer and circuit resistance C: bimonthly education sessions (offered to E as well)	70% max. HR, weight-training intensity: 80% 1RM	90–120 (15–30 min arm erg.)	2	39	1RM Max. force test E:↑ * ^, C: ↑ Power output (W) Submax. arm ergometer test 40%: E: ↑, C: ↑ 60%: E: ↑, C: ↑ 80%: E: ↑*, C: ↓
Hjeltnes *et al.*[36] (D&B = 12)	5	C5–C7	35.0 ± 3.0	10.2 ± 3.4	FES leg cycling	Initial: 6 W End: 6–18 W	30	7	8	Power output (W) Graded arm ergometer test: ↑ Electrical stim. leg cycle test: ↑ Muscle CSA Total: ↑* DEXA scan Lean body mass: ↑* Fat mass: ↓*
Hjeltnes *et al.*[74] (D&B = 13)	5	C5–C7	35 ± 3 (s.e.)	10 ± 3 (s.e.)	FES leg cycling	50 r.p.m.	30 (and/or to fatigue)	7 (1 session per day for 3 days; 2 sessions per day for 2 days)	8	Training program measures Work output: ↑ (#) Max. work during 1 bout: ↑ (#) Vastus lateralis (muscle biopsy) Type I: ↑, type IIa: ↑, type IIb: ↓
Hooker *et al.*[75] (D&B = 13)	18	C5–T11	30.6 ± 0.45 (s.e.)	6.1 ± 0.25 (s.e.)	FES leg cycling ergometer (FES-LCE)	50 r.p.m.	30	3	12–16	Power output (W) Graded FES-LCE: ↑* Max. exercise test: ↔ Oxygen uptake (VO_2) Graded FES-LCE: ↑* Max. exercise test: ↔
Hooker and Wells[45] (D&B = 9)	11 LI:6 MI:5	LI: C5–T7 MI: C5–T9	31.3 ± 4.2	12.9 ± 6.8	Wheelchair ergometer LI: Low intensity MI: Moderate intensity	LI:50–60% Max HR MI: 70–80 Max HR	20	3	8	Power output (W) Max. exercise test: LI: ↑, MI: ↑ Oxygen uptake (VO_2) Max. exercise test: LI: ↑, MI: ↑ Submax. exercise test 5 W: LI: ↔, MI: ↓ 10W: LI: ↓, MI: ↓ 15W: LI: ↓, MI: ↑
Jacobs[76] (D&B = 15)	18 RT:9 ET:9	T6–T10	RT: 33.7 ± 8.0 ET: 29.0 ± 9.9		RT: resistance training ET: endurance training (arm crank)	RT: 60–70% 1RM ET:70–85% max. HR	30	3	12	Isotonic muscle strength RT: ↑*, ET: ↓ Power output (W)—Wingate test PO_{peak}: RT: ↑*^, ET: ↑* PO_{mean}: RT: ↑*, ET: ↑* Oxygen uptake (VO_2) Max. exercise test: RT: ↑*, ET: ↑*

Table 3 Continued

Reference	*n*	*Lesion range*	*Age (years), mean ± s.d.*	*Time since injury (years), mean ± s.d.*	*Training program characteristics*					*Outcomes*
					Type	*Intensity*	*Time (min)*	*Frequency (times per week)*	*Duration (weeks)*	
Jacobs *et al.*[77] (D&B = 14)	15	T4–T11	28.2 ± 6.8	3.7 ± 3.0	FES ambulation (parastep-1)	Chosen by SS	Chosen by SS	3	11	Muscle strength Isometric grip strength: ↑ Dynamic chest press: ↓ Power output (W) Peak exercise test: ↑* Oxygen uptake (VO_2) Peak exercise test: ↑*
Jacobs *et al.*[78] (D&B = 15)	10	T5–T12	39.4 ± 6.0	7.3 ± 6.0	Circuit resistance training	Weeks 1 and 2: 50%1RM Week 3: 55%1RM Week 4: 60%1RM	40–45	3	12	Muscle strength 1RM max. strength: ↑* Isokinetic torque: Peak: Con.: ↑*, Ecc.: ↑* avg.: con.: ↑*, ecc.: ↑* Power output (W) Max. arm ergometer test: ↑* Oxygen uptake (VO_2) Max. Arm ergometer test: ↑*
Janssen and Pringle[79] (D&B = 15)	12	C4–T11	36 ± 16	11 ± 9	Interval training program with NMES leg cycle ergometer	Customized to each SS	25–30	2–3	6	Peak muscle torque 1st contraction: ↑* 20th contraction: ↑* Power output (W) Max. exercise test: ↑* Oxygen uptake (VO_2) Max. exercise test: ↑*
Jayaraman *et al.*[80] (D&B = 11)	5	C4–T4	41.4 ± 13.9	20.0 ± 11.5 months	BWSTT	40% BWS initially; 2.0–2.8 mph	30	5	9	Peak torque Knee extensor: LI: ↑, MI: ↑ (#) Plantar flexors: LI: ↑, MI: ↑ (#) Training characteristics % BWS: ↓ (#), walking speed: ↑ (#)
Kakebeeke *et al.*[81] (D&B = 12)	1	C6	31	3	FES leg cycling	Until exhaustion	Pre-3 months: 210 min per week; 4 months post: 310 min per week	Pre-3 months: 3–4 4 months - Post: 5	52	Power output (W) Incremental exercise test: ↑* Oxygen uptake (VO_2) Incremental exercise test: ↑*
Klose *et al.*[33] (D&B = 17)	16	T4–T11	28.4 ± 6.6	4.0 ± 3.5	FES ambulation (parastep-1)	Chosen by SS	Chosen by SS	3	11	Training program measures Distance: ↑* Duration: ↑* Pace: ↑* Body composition Thigh girth: ↑* Calf girth: ↑* Thigh skinfold: ↑* Body weight: ↑ Lean tissue mean: ↑* Muscle CSA thigh: ↑*
Krauss *et al.*[82] (D&B = 12)	8	C7–L1	32 ± 2 (s.e.)	13 ± 2 (s.e.)	FES leg ergometry (CFES-LE) and hybrid ergometer (HE; CFES-LE+arm ergometry)	CFES-LE: customized to each SS HE: same as CFES-LE and 50% peak power output from max. arm ergometer test	30	3	12: 6 weeks CFES-LE; 6 weeks HE	Oxygen uptake (VO_2) Graded FES-LCE test: ↑* Max. arm ergometry test: ↑* Graded HE test: ↑* Work load FES-LCE: ↑* HE: ↑*

Table 3 Continued

Reference	n	Lesion range	Age (years), mean ± s.d.	Time since injury (years), mean ± s.d.	Training program characteristics: Type	Intensity	Time (min)	Frequency (times per week)	Duration (weeks)	Outcomes
Lui et al.[83] (D&B = 13)	18	C3–T12	40.0 ± 11.3	3.2 ± 2.1	FES leg cycling	45 r.p.m.	30	3	8	Isometric knee extension Peak torque: ↑* Body composition Body weight: ↑ Fat mass: ↑ Lean mass: ↑* % Fat mass: ↓ BMI: ↑ Leg Girth R thigh: ↑* L thigh: ↑* R calf: ↑ L calf: ↑
Mahoney et al.[41] (D&B = 11)	5	C5–T10	35.6 ± 4.9	13.4 ± 6.5	NMES leg resistance	Increased 0.9–1.8 kg per week		2	12	Quad CSA Right: ↑* Left: ↑*
Melchiorri et al.[42] (D&B = 15)	10	T8–T10	34.2 ± 4.0	8.0 ± 3.0	Vibration exercise—elbow flexion	30 Hz	5 min (5 × 60 min bouts per session, with 60-s rest intervals in between bouts)	5	12	Muscle strength Forearm flexion avg. force Dom.: ↑, N_{dom}: ↑ Power output (W) Forearm flexion 5% load: Dom.: ↑*, N_{dom}: ↓ 8% load: dom.: ↑*, N_{dom}: ↑ 10% load: dom.: ↑*, N_{dom}: ↑ 15% load: dom.: ↑, N_{dom}: ↑ DEXA Arm fat mass: R: ↑, L: ↓ Arm fat free mass: R: ↑*, L: ↑*
Mohr et al.[37] (D&B = 14)	10	C6–T4	35.3 ± 7.3	12.9 ± 7.3	FES cycle ergometer	1/8–7/8 kp; 50 rev/min–max.	30	3	52	Oxygen uptake (VO_2) Progressive exercise test: ↑* Exercise performance Training program measures: ↑* Body composition Thigh CSA (MRI): ↑* VL muscle biopsy (#) Type I: ↑ Type IIb: ↓ Type IIa: ↑ Thigh girth: ↑*
Nash et al.[84] (D&B = 16)	7	T5–T12		13.1 ± 6.6	Circuit resistance training	Weeks 1 and 2: 50%1RM Week 3: 55%1RM Week 4: 60%1RM	40–45	3	16	1RM max. force: ↑* Power output (W) Graded arm ergometer test Peak: ↑*, mean: ↑*
Needham-Shropshire et al.[85] (PEDro = 8)	34	Cervical	G1:24.0 G2:22.0 G3:24.0	G1: 6.0 G2: 9.0 G3: 4.0	G1: NMES-assisted arm erg (8 weeks) G2: NMES-assisted arm erg (4 weeks)+arm erg alone (4 weeks) G3: arm erg alone (8 weeks—control)	60 r.p.m.	4 × 5 min = 20 min with 3 min between bouts	3	8	Triceps manual muscle grade GI: ↑ ^, G2: ↑ ^, G3: ↑ ^ sig. difference from G3

Table 3 Continued

Reference	n	Lesion range	Age (years), mean ± s.d.	Time since injury (years), mean ± s.d.	Training program characteristics					Outcomes
					Type	*Intensity*	*Time (min)*	*Frequency (times per week)*	*Duration (weeks)*	
Nilsson *et al.*[86] (D&B = 12)	7	C6–T12	36.4 ± 10.3	9.8 ± 4.4	Arm ergometer and weight training	50 r.p.m.; 2 submaximal bouts, 1 maximal bout (until exhaustion)	12 (3 × 4 min)	3	7	Dynamic muscle strength (triceps): ↑* Oxygen uptake (VO_2) Maximal effort test: ↑* Exercise performance: ↑*
Ornstein *et al.*[87] (D&B = 5)	6				Aerobic swimming	70–85% max. HR	5–35	3	8	Graded ergometer Performance time: ↑*
Pacy *et al.*[31] (D&B = 10)	4	T4–T6	Range: 20–35	Range: 1–8	FES *Regimen 1(R1)*: straight leg raising *Regimen 2(R2)*: FES-biking (leg ergometer)	R1: 1.4–11.4 kg R2: 50 r.p.m. (0–18.75 W)	R1:15 min per leg (total 30 min); R2:15 min	5	R1: 10; R2: 32; total: 42	Body composition Muscle CSA: ↑*, fat CSA: ↓* Body weight: ↑
Petrofsky *et al.*[88] (D&B = 13)	90	T4–T11	24.9		FES leg resistance (weights)	Groups G–I test extension:flexion:rest cycle (s) G: 6:6:6; H: 3:3:6; I: 1:1:6	Groups A–C test length of session. A: 5; B: 15; C: 30	Groups D–F test no. of sessions per week D: 1; E: 3; F: 5	10	Isometric quad. strength Length of session: A/B: ↑, C: ↑ ^, no. of days per week: D:↑, E/F: ↑ ^ ext.:flex:rest cycle: G/I: ↑, H: ↑ ^ Work capacity Length of session: A: ↑, B: ↑ ^ C: ↑^, no. of days per week: D: ↑, E/F: ↑ ^ Ext.:flex cycle: G/I: ↑, H: ↑ ^
Pollack *et al.*[89] (D&B = 11)	11	C4–T6	29	67 months	FES leg program *Phase 1:* 3 lbs weight lift (45 times) *Phase 2:* unloaded leg ergometer cycle *Phase 3:* continuous leg ergometer cycle at variable resistances	*P1 and P2:* customized to SS. Once SS could cycle unloaded ergometer for 5 min, graduate to P3. *P3:* customized to SS		3	13–28	Oxygen uptake (VO_2) Maximal exercise test: ↑*
Rodgers *et al.*[90] (D&B = 10)	10	C4–T10	38.3 ± 12.9	6.4 ± 6.1	FES-induced knee extension (KE)	0.5–15.0 kg		3	12	Quad. muscle strength (kg per no. of repetitions) Left: ↑*, right: ↑* Max. load resistance Left: ↑*, right: ↑* Thigh skinfold thickness Left: ↓, right: ↓ Thigh girth Left: ↓, right: ↓
Rodgers *et al.*[43] (D&B = 11)	19	T3–L5	44.0 ± 11.0	17.0 ± 10.0	Strengthening, stretching and aerobic exercise	Strengthening and stretching customized to SS; aerobic exercise at 60% max. HR		3	6	Muscle strength Hand grip: ↑ Training program measures: ↑* Power output (W) Max. exercise test: ↑* Oxygen uptake (VO_2) Max. exercise test: ↑

Table 3 Continued

Reference	n	Lesion range	Age (years), mean ± s.d.	Time since injury (years), mean ± s.d.	Training program characteristics: Type	Intensity	Time (min)	Frequency (times per week)	Duration (weeks)	Outcomes
Sloan *et al.*[38] (D&B = 14)	9	C5–L1	27.3 ± 11.7	40.1 ± 47.9 months	FES cycling	Customized to SS	Gradual progress to 30 min per session	3	12	Isometric strength Voluntary: ↑* Stimulated: ↑* Isokinetic strength Concentric peak: ↔ Concentric avg.: ↑* Eccentric peak: ↔ eccentric avg.: ↔ Muscle CSA Quads: ↑* Hamstrings: ↑ Total midthigh: ↑*
Stewart *et al.*[35] (D&B = 10)	9	C4–T12	31.0 ± 3.0	8.1 ± 2.0	BWSTT	Initial: BWS = 65 ± 3%; $<0.6\,km\,h^{-1}$		3	26	Training program measures %BWS: ↓* Walking velocity: ↑* Duration of session: ↑* Muscle biopsy Mean fiber area: ↑* Type I fibers: ↑ * Type IIa fibers: ↑ * Type IIx fibers: ↔
Taylor *et al.*[29] (D&B = 13)	10 E: 5 C: 5		E:27.2 ± 6.7 C:33.4 ± 16.4	E: 7.2 ± 4.4 C: 15.8 ± 13.9	E: arm ergometer E/C: recreational basketball	50 r.p.m.; 80% max. HR	30	5	8	Oxygen uptake (VO_2) Max. exercise test: E:↑*, C: ↑ Body composition Body weight: E:↓, C: ↔ Body fat: E:↑, C: ↑ Arm circumf.: E: ↑, C: ↔
Tordi *et al.*[25] (D&B = 13)	5	T6–L4	27.0 ± 8.1		Wheelchair ergometer interval	SWEET: Successive 5-min work bouts: 4 min mod (50% MTP), 1 min heavy (80% MTP)	30	3	4	Power output (W) Max. progressive exercise test: ↑* Oxygen uptake (VO_2) Max. progressive exercise test: ↑* Constant load exercise test: ↑* Constant load exercise test Time to exhaustion: ↑* Total mechanical work: ↑*
Wheeler *et al.*[91] (D&B = 17)	6	C7–T12	42.5 ± 17.9	13.8 ± 11.6	FES rowing hybrid training	75–80% Peak VO_2	30	3	12	Oxygen uptake (VO_2) Max. exercise test Upper extremity: ↑ Lower extremity: ↑ Hybrid: ↑* Distance rowed: ↑*
Whiting *et al.*[92] (D&B = 9)	2	A: C6–C7 B: C5–C6	A: 21 B: 33	A: 3.5 B: 5.0	Wheelchair ergometer	Initial: 75% HR Progressive increase: 85%HR	20	3	8	Oxygen uptake (VO_2) Max. exercise test: A: ↓ B: ↑ (#)
Wirz *et al.*[93] (D&B = 15)	20	C3–L1	40.0 ± 14.0	5.9 ± 4.9	Robot-assisted BWSTT with drive gait orthosis	37 ± 7% BWS; $0.55 \pm 0.03\,m\,s^{-1}$	45	3–5	8	Functional performance 10 m walking test: ↑* 6 m walking test: ↑* Timed up and go test (time): ↓*

Table 3 Continued

Reference	n	Lesion range	Age (years), mean ± s.d.	Time since injury (years), mean ± s.d.	Training program characteristics					Outcomes
					Type	*Intensity*	*Time (min)*	*Frequency (times per week)*	*Duration (weeks)*	
Yim *et al.*[94] (D&B = 13)	11	T8–T12	30.9 ± 7.9	20.6 ± 12.5 months	Wheelchair ergometer	$>3\,km\,h^{-1}$; $>80\%$ max. HR	30 (3 × 10 min bouts, 5 min rests in between bouts)	3	5	Isokinetic test (shoulder and elbow flexion/extension) Peak torque: ↑ * Total work: ↑ * 100 m wheelchair propulsion Test (time): ↓*

Symbols: *, Sig. difference pre–post, ^, sig. difference between groups (i.e., E versus C), #, sig. not indicated.
Abbreviations: AB, able-bodied; ADL, activities of daily living; BWS, body weight support; BWSTT, body weight-supported treadmill training; C, control group; CSA, cross-sectional area; D&B, Downs & Black quality assessment tool; E, experimental group; FES, functional electrical stimulation; HR, heart rate; HRR, heart rate reserve; MVC, maximal voluntary contraction; NMES, neuromuscular electrical stimulation; PEDro, Physiotherapy Evidence Database; 1RM, 1 repetition maximum; RPE, rating of perceived exertion; SS, subject.

Power output: Maximal power output achieved during a maximal exercise test is a component of physical capacity that provides an indirect indicator of muscle strength and aerobic capacity. Arm ergometry training programs of 6 and 8 weeks duration have produced significant improvements in maximal power output, regardless of training intensity.[11,12] The addition of arm ergometry training to inpatient rehabilitation has been shown to significantly increase peak power in patients with paraplegia and tetraplegia.[13] Mixed exercise programs, including strength, aerobic and mobility training, significantly increased peak power output following 16 weeks of training.[14] Wheelchair ergometry has also been shown to have a similar effect, resulting in significant increases in peak power output following 6 weeks of training.[10]

Muscle strength. Decrease in muscle strength—the result of pronounced muscle atrophy and decreased neural drive—is one of the most significant and rapidly occurring consequences post SCI. Four studies included a measure of muscle strength. Significant increases in weight lifted and number of repetitions completed during various upper-body exercises were observed following a 16-week mixed exercise training program that incorporated mobility, strength and aerobic training.[14] The addition of 30 min of arm ergometry, 3 × per week, to inpatient rehabilitation programs also resulted in significant increases in muscle strength scores by more than 6 points in five upper-extremity muscles.[13]

Body composition. In people with acute SCI, lean mass is only 60–65% that of able-bodied controls and body fat can increase to levels corresponding to 100–113% of that of controls.[15] Reduced muscle mass and increased fat mass are both considered risk factors for secondary health complications and chronic disease.

Body weight: Only three level 4 studies examined body weight as an outcome. One study[16] reported no significant changes in body weight or body mass index following a 6-week arm ergometry program. Likewise, an arm ergometry program during 4 months of inpatient rehabilitation had no significant effect on body weight.[13] Similar results were noted following a 16-week mixed exercise program.[14] When interpreting these non-significant changes, it is important to note that the maintenance of body weight for people who are wheelchair dependent is an important clinical finding given the fact that obesity is a significant secondary complication in this group.[17]

Lean (muscle) and fat mass: Two level 4 studies examined body composition changes. Giangregorio *et al.*[15] examined the effects of a 2 × per week body-weight-supported treadmill training (BWSTT) program and reported increases in thigh and calf muscle cross-sectional area (4–57%) and increased leg fat. Another study involving arm ergometry showed no significant changes in lean or fat mass.[16]

Table 4 Summary of studies and evidence for each fitness component (acute spinal cord injury)

Fitness component	*Outcome*	*No. of studies*	*Description of studies*	*Summary of evidence*
Physical capacity		6		
	Power output (PO)		*Aerobic exercise training programs:* These six studies included 56 participants, from a variety of countries and regions, in aerobic exercise programs. Median D&B = 15. For the only RCT, $n = 6$ and PEDro = 7.	Significant increases in PO were seen in the level 4 studies with 3 × per week exercise programs and intensities ranging from 40 to 80% HRR. The single level 1 RCT also showed an increase in PO in a group that trained at an intensity of 40–50% HRR and a group that trained at 70–80%, but reported no difference between the groups.
	Aerobic capacity		*Aerobic exercise training programs:* These five studies involved 43 participants from a variety of countries and regions in aerobic exercise programs. Median D&B = 15.5. For the only RCT, $n = 6$ and PEDro = 7.	Significant increases in VO_{2peak} were seen in level 4 studies with training 3 × per week, and intensities that ranged from 40 to 80% HRR. The level 1 RCT also showed significant increases in VO_{2peak} with an 8-week training program, 3 × per week, and intensity of 40–50% HRR and 70–80% HRR, with a greater increase in the group training at a higher intensity.
Muscle strength		4		
			Exercise training programs: These three studies involved 86 participants from a variety of countries and regions, in aerobic, strength or combination exercise programs. Median D&B = 16. For the only RCT, $n = 31$ and PEDro = 7.	The level 1 RCT reported non-significant increases in isometric torque with a training program 3 × per week for 8 weeks. Significant increases in strength were observed in the level 4 studies with a training frequency of 3 × per week, for 16 weeks, at 40–80% max. HR.
			Functional electrical stimulation: A single RCT evaluated the addition of muscle stimulation to resistance training of the wrist extensor muscle with $n = 32$, and PEDro = 7.	This level 1 study found no significant increases in muscle strength using a training frequency of 3 × per week for 8 weeks.
Body composition		4		
	Body weight		*Exercise training programs:* These three studies had a total *n* of 44 and used training programs that combined aerobic and resistance exercise. Median D&B = 16.	No significant changes in muscle or fat mass were reported in this level 4 study.
	Muscle and fat mass		*Aerobic and resistance training programs:* One study used a mixed aerobic and resistance training program to examine these outcomes; $n = 21$ and D&B = 14.	No significant changes in body weight were reported in these level 4 studies.
			Other: One study examined changes in lean and fat mass using a BWSTT program; $n = 4$, D&B = 16.	Muscle mass and leg body fat increased but significance was not reported in this level 4 case series study.
Functional performance		6		
	Wheelchair skills		*Exercise training programs:* These two studies had a total *n* of 14. One study used strength and aerobic-training and one case study used BWSTT. Median D&B = 13.5.	A decrease in time to complete a wheelchair skills test was reported in one level 4 study that used a training program with an intensity of 40–80% max. HR, for 15–120 min sessions, 3 × per week for 16 weeks. No significant changes in functional wheeling were reported in the level 5 case study.
	Walking		*Other:* One pre–post and one case study evaluated the effects of BWSTT. Total $n = 5$, median D&B = 13. Two RCTs utilized BWSTT, $n = 250$, median PEDro = 6.	Neither of the RCTs reported significant changes in any walking measures. The level 5 study reported an increase in gait speed with a 3 × per week training program over 6 weeks.

Abbreviations: BWSTT, body weight-supported treadmill training; D&B, Downs & Black quality assessment tool; HRR, heart rate reserve; PEDro, Physiotherapy Evidence Database; RCT, randomized controlled trial.

Table 5 Summary of studies and evidence for each fitness component (chronic spinal cord injury)

Fitness component	*Outcome*	*No. of studies*	*Description of studies*	*Summary of evidence*
Physical capacity		46		
	Power output		*Combined resistance and arm ergometry exercise*: These studies had a total of 58 participants from a variety of countries and regions and combined arm ergometry training with either traditional resistance training (2 studies) or circuit resistance training (2 studies). Two RCTs were conducted with a median PEDro score of 6.5, and two pre–post exercise studies had a median D&B = 15.5.	Level 1 and 4 studies have shown the combination of resistance and aerobic training to improve power output of the upper limbs. While 3 of these studies showed the benefits of exercise 3× per week, one RCT showed 2× per week exercise to improve arm ergometry power output after 9 months. The other RCT showed the combination of circuit resistance training and arm ergometry to increase arm ergometry power output after 12 weeks.
			Wheelchair exercise: One study ($n=8$; D&B = 11) examined the effects of 8 weeks of wheelchair exercise training, 3× per week, on upper limb power output.	This single level 4 study showed non-significant improvements in upper limb power output.
			Functional electrical stimulation: These studies included a total of 89 participants and utilized FES-cycling exercise, FES-ambulation exercise or a hybrid of FES-cycling exercise and arm ergometry. Median D&B = 13.	A level 2 non-randomized trial and level 4 pre–post studies showed lower limb power output improved with as little as 8 weeks of FES-cycling exercise, 3 sessions per week.
	Aerobic capacity		*Arm ergometry exercise*: These studies had a total of 44 participants from a variety of regions. All studies employed manual arm ergometry as the mode of exercise training, for a duration between 5–12 weeks. Median D&B = 10.	In these level 4 studies, arm ergometry has been shown to be very effective in improving aerobic capacity. Most of these studies employed a thrice-weekly exercise training program and benefits were realized in as little as 5 weeks. One study employed training 5× per week and aerobic capacity improved, but not more so than in studies using a 3× per week training schedule.
			Wheelchair ergometry exercise: These studies had a total of 40 participants from a variety of regions. All studies employed manual wheelchair ergometry as the mode of exercise training for a duration between 4–8 weeks. Median D&B = 11.	This evidence consists of level 4 and 5 studies. Most have shown improvements in aerobic capacity following 3× per week training for as little as 4 weeks. One study used a 5× per week training schedule and showed greater than usual improvements in aerobic capacity.
			Combined resistance and arm ergometry exercise: These three studies included a total of 36 participants from a variety of regions. All three studies employed a combination of resistance training and arm ergometry exercise as the mode of exercise, for a duration between 6–12 weeks. Two of the studies were level 4 trials with a median D&B of 12, while the other was a RCT with a PEDro score of 7. The 2 level 4 studies employed traditional resistance training, while the RCT employed circuit resistance training.	These three level 4 trials produced conflicting results; two studies (one level 4 study, and the RCT) showed significant improvement in aerobic capacity following training 3× per week for 7 and 12 weeks, while the other (level 4 study) showed no improvement following 3× per week training for 6 weeks.
			Resistance training exercise: One study with 9 participants and a D&B score of 15 examined the effects of 12 weeks of resistance training 3× per week on aerobic capacity.	Although resistance training is not traditionally used to improve aerobic capacity, this level 4 study yielded significant improvements in aerobic capacity. Further, the magnitude of improvement was comparable to that seen in most other exercise studies.
			Functional electrical stimulation: These studies include a total of 139 participants and utilized FES-cycling	In these level 4 and 5 studies, FES exercise has shown to be very effective in improving aerobic

Table 5 Continued

Fitness component	*Outcome*	*No. of studies*	*Description of studies*	*Summary of evidence*
			exercise, FES-ambulation exercise, FES-rowing exercise or a combination of FES-cycling and arm ergometry (hybrid exercise). Median D&B = 13.	capacity in as little as 4–6 weeks. Most of these studies have employed an exercise schedule 3 × per week, although there is evidence with FES ambulation that training 2 × per week is sufficient for improvement.
Muscle strength		22		
			Combined resistance and arm ergometry exercise: These studies included 91 participants from a variety of countries and regions participating in mixed aerobic and strength-training programs, circuit resistance training and individual muscle strength training. Median D&B = 15. The only RCT involved 23 participants and scored 5 on the PEDro.	Level 4, pre–post training studies consistently show that participation in any form of exercise training that 'overloads' the muscle will result in increases in muscle strength. While most studies have used training frequencies of 3 × per week, the level 1 RCT demonstrated significant improvements in muscle strength with a frequency of 2 × per week. Training intensities ranged between 50–80% 1RM.
			Functional electrical stimulation: These studies included 219 participants from a variety of countries and regions utilizing FES cycling, FES-assisted walking or FES-assisted resistance training. Median D&B = 13.5; the one RCT (n = 34) scored 8 on the PEDro.	Level 4, pre–post training studies utilizing FES show that muscle strength can significantly increase in the paralyzed muscles after as little as 8 weeks of training, 3 × per week. There is level 1 evidence that FES-assisted arm ergometry training is more effective in improving triceps strength than arm ergometry alone.
			Other: Changes in muscle strength have been assessed following BWSTT (n = 5), shoulder-Kayak ergometry (n = 10) and wheelchair ergometry (n = 11). The median D&B score was 12.	Level 4, pre–post training studies have shown that specialized ergometry can lead to significant improvements in muscle strength. Improvements were non-significant in the BWSTT study.
Body composition		24		
	Body weight		*Resistance and aerobic exercise:* These studies included 32 participants from a variety of countries and regions participating in mixed aerobic and strength-training programs, or arm ergometry training programs. Median D&B = 11.	All of these level 4 studies reported non-significant increases or decreases in body weight and utilized a training frequency of 3 × per week with an intensity ranging from 40 to 80% max. HR.
			Functional electrical stimulation: These studies included 38 participants from a variety of countries and regions utilizing FES cycling, FES-assisted walking or FES-assisted resistance training. Median D&B = 13.	All of these level 4 studies reported non-significant increases or decreases in body weight. The frequency of training was either 3 or 5 × per week.
			Other: One study measured changes in body weight following a combined locomotor training program (n = 1, D&B = 11), and another study used wheelchair treadmill training (n = 7, D&B = 12).	In these level 4 and 5 studies, exercise training did not have any significant effects on body weight.
	Muscle mass		*Resistance exercise:* These two studies utilized lower body resistance training (n = 3, D&B = 11) or vibration resistance training (n = 10, D&B = 15).	One level 4 study of vibration exercise reported significant increases in fat free mass with training 5 × per week for 12 weeks. No other significant changes in lean tissue mass were reported.
			Functional electrical stimulation: These studies included 104 participants from a variety of countries and regions utilizing either FES cycling, FES assisted ambulation, or FES-assisted resistance training. Median D&B = 13.	A level 2 study reported significant increases in quadriceps cross-sectional area with a treadmill training frequency of 2 × per week for 26 weeks. Level 4 studies have also noted significant increases in lean body mass and muscle cross-sectional area with training program frequency ranging from 2 to 7 × per week.

Table 5 Continued

Fitness component	*Outcome*	*No. of studies*	*Description of studies*	*Summary of evidence*
			Other: With a total of 24 participants, 4 studies have examined changes in lean tissue mass using some alternative training programs such as BWSTT and mixed locomotor training. Median D&B = 10.5.	Two level 4 studies reported significant increases in thigh and calf muscle cross-sectional area and an increase in whole-body lean tissue mass following a BWSTT program 3 × per week.
	Fat Mass		*Resistance exercise:* There was a single study that used elbow flexion exercises ($n=10$; D&B = 15).	No significant changes in fat mass were reported in this level 4 study.
			Functional electrical stimulation: These studies included 43 participants from a variety of countries and regions. They utilized either FES cycling, resistance training or ambulation. Median D&B = 11.	Two level 4 studies reported a significant decrease in fat mass with a training program 5–7 × per week, 30 min per session, 6–18 W. Increases in thigh skinfold measures have also been reported in another pre–post study 3 × per week, 11 weeks, intensity chosen by subject.
			Other: Studies involving BWSTT ($n=13$, D&B = 18) and a mixed locomotor training program ($n=1$, D&B = 11) have examined changes in fat mass.	No significant changes in fat mass were reported in these level 4 and 5 studies.
Functional Performance		24		
	Wheelchair propulsion and skills		*Resistance and aerobic exercise:* One study ($n=19$; D&B = 11) combined stretching and strengthening with rowing ergometry exercises.	In this level 4 study, significant improvements in maximum power output during wheelchair propulsion were reported after 6 weeks of ergometry performed 3 × per week at a moderate intensity.
			Aerobic exercise: These studies included 74 participants from various countries and regions. Training protocols consisted of either arm, wheelchair or rowing ergometry. Median D&B = 12.	These level 4 studies consistently showed ergometry exercise resulted in significant improvements in propulsion. One showed significant improvements in wheelchair skills. Most studies trained 3 × per week, at moderate–heavy intensities.
	Walking		*Step training*: These studies had a total of 162 participants, from a variety of countries and regions. Training modalities included treadmill training (BWSTT, robotic assisted, manually assisted, FES assisted), FES-assisted overground walking training. Measures included overground walking and treadmill training parameters (speed, distance, duration, %BWSTT required). Median D&B = 15. There was one RCT, PEDro = 6.	Findings were mixed in the level 4 studies. Most found significant improvements in overground walking following BWSTT both with and without FES. Changes in treadmill training parameters emerged in most, but not all studies, depending on the parameters measured. Training ranged from 2 to 5 × per week; intensity varied considerably and was often individually determined. The level 1 RCT showed significant improvements in overground walking speed and treadmill training speed across four types of BWS step training prescribed 5 × per week at an individualized intensity.
			Strength training: one study (n = 3, D&B = 3) utilized lower-body strength training and plyometrics.	In this level 4 study, improvements in overground walking (significance not reported) were noted after 12 weeks of training, 2–3 × per week at 70–85% of 1RM.
	Standing		*Step training:* A single case study examined changes in standing following BWSTT. D&B = 11.	This level 5 study showed progressive BWSTT, 3 × per week, led to improvements in the ability to stand with a walker.

Abbreviations: BWSTT, body weight-supported treadmill training; D&B, Downs & Black quality assessment tool; FES, functional electrical stimulation; PEDro, Physiotherapy Evidence Database; RCT, randomized controlled trial; 1RM, 1 repetition maximum.

Functional performance. Post SCI, people often lack sufficient fitness to perform basic activities of daily living.[4] Poor functioning can compromise independence and QoL.[4]

Wheelchair skills: In a level 4 study of acute and chronic SCI patients, time to complete various wheelchair skills significantly decreased following an exercise program with mobility-, strength- and aerobic-training components.[14] Similar results were reported in a level 5 study that used a primarily aerobic-based training program.[18]

Walking measures: Level 1, 4 and 5 studies have evaluated the effects of BWSTT in people with acute SCI, with inconsistent results for walking outcomes. A single level 1 study demonstrated improvements on a variety of clinically relevant walking outcomes,[17,18] supported by level 4 studies showing increased gait speed.[13,16] However, improvements on these outcomes were not significantly different as compared with conventional intensive overground locomotor training. Non-significant improvements in walking cadence,[19] stride length[19] and percentage of body-weight support required[15] have also been reported.

Studies of people with chronic SCI

Physical capacity. Physical capacity—reflected in measures of power output and aerobic capacity—is relevant to the independence, health and QoL of individuals with SCI. Power output, for instance, can impact the ability to effectively perform transfers and propel one's wheelchair on inclines and other challenging surfaces. Aerobic capacity is pertinent for cardiovascular health, functional independence and fatigue resistance. Forty-six studies have investigated the effects of exercise on power output and aerobic capacity. Although the magnitude of improvements varies across studies, exercise appears to be effective in improving these fitness outcomes.

Power output: Sixteen studies reported on changes in power output. Most were level 4 studies. However, there were two level 1 RCTs and a level 2 non-randomized trial. Taken together, the 16 studies provide strong evidence that combined resistance and aerobic exercise, and functional electrical stimulation (FES)-assisted exercise, produced significant improvements in power output. Most studies prescribed exercise 3 × per week for 6–12 weeks, although two studies showed particularly large improvements in lower limb power output following 1 year of FES cycling, 3–5 × per week.[20,21] Unfortunately, it is difficult to pinpoint the exercise intensity required for improvements because the majority of studies (11 of 16) employed FES exercise; stimulation parameters vary widely among these studies and progression typically occurs as individually tolerated. However, moderate-intensity arm ergometry exercise (70–80% max HR or 50% HR reserve) combined with resistance training (progressed to repetitions with 70–80% of the one repetition maximum) seems sufficient for long-term improvements. When max HR cannot be confidently estimated (for example, in individuals with cervical injuries and thus, blunted HR responses to exercise), exercise intensities of 3–4 on the Borg scale of perceived exertion may be used. Of note, one level 1 RCT showed resistance and aerobic exercise performed 2 × per week at a moderate intensity led to significant increases in power output over a 39-week study.[22]

Aerobic capacity: Thirty studies reported on changes in aerobic capacity; virtually all were level 4 or 5 studies. Across these studies, it was clear that FES exercise of various forms (cycling and ambulation), as well as arm ergometry and wheelchair exercise, produced significant improvements in aerobic capacity. One level 4 study showed that 3 × per week circuit resistance exercise combined with arm ergometry improved aerobic capacity following 12 weeks of training.[22] Most of the studies prescribed exercise 3 × per week for 6–12 weeks, although studies employing as little as 4–5 weeks of exercise have also shown improvements.[23–25] Again, because almost half of these studies (13 of 30) employed FES exercise, it is difficult to discern the exercise intensity required for improvements in aerobic capacity. It is evident that moderate arm ergometry or wheelchair exercise at an intensity between 60–80% of max HR, or 60–65% VO_{2peak}, seems sufficient to improve aerobic capacity.

There are a few important considerations when prescribing exercise to improve power output and aerobic capacity in individuals with SCI. First, when deciding between voluntary versus stimulated exercise, the potential for arm ergometry to improve power output and aerobic capacity depends in large part on the motor function in the upper limbs. For those with little to no arm function, a stimulated form of exercise such as FES is probably more effective. Second, when employing FES exercise, it is still unclear as to which form (for example, cycling, ambulation) is the most effective in improving aerobic capacity, although all have shown benefit.

Muscle strength. Muscle strength is a highly relevant fitness outcome in the chronic SCI population, as improvements in strength will have a significant impact on the ability to perform activities of daily living (for example, transferring, wheeling). If increased strength is associated with increased muscle mass, such changes can also have metabolic benefits. Numerous studies have evaluated the efficacy of various exercise-training protocols for improving muscle strength. These protocols can be categorized as 'voluntary' strength training (that is, using non-paralyzed muscles), and those utilizing some form of electrically stimulated exercise of paralyzed muscles.

Voluntary strength training: Eleven studies examined changes in strength following training of non-paralyzed muscles. With the exception of a single level 1 RCT, all were level 4 studies. Across studies, it was clear that the muscles responded to training in a similar manner as would be expected in the able-bodied population. Specifically, circuit resistance training paradigms, BWSTT, arm ergometry and training with specialized equipment (for example, shoulder kayak ergometry) significantly increased muscle strength of trained limbs after as little as 5 weeks. While the majority of studies used training volumes incorporating 3 × per week frequencies, significant strength changes were demonstrated with 2 × per week training in a high-quality RCT[22] and a low-quality pre-post study.[26] For studies employing resistance training (for example, lifting weights), training intensities varied between 50–80% of the one repetition maximum. There was clear evidence from the level 1 RCT that twice-weekly strength training employing 2–3 sets at 70–80% of the one repetition maximum is effective in increasing voluntary muscle strength.[22]

Functional electrical stimulation: FES is traditionally used in the SCI population to activate muscles that can no longer be fully activated voluntarily. Of the 11 FES studies reviewed, one was level 2 and the remainder were level 4 studies. There was a wide variety in the type of FES training employed (cycling, walking and resistance training) across studies. Most studies reported significant increases in leg (knee extensors, hip flexors and/or knee flexors) or arm strength following training programs of 6–12 weeks. Training frequency in the majority of studies was 3 × per week. Despite the consistent finding that FES-assisted training of the paralyzed musculature enhances strength, the heterogeneity in FES training modes makes it impossible to comment on the intensity of training needed to elicit improvements. It should also be noted that FES is not tolerated equally by all individuals with SCI, so it may not be appropriate for everyone.

Body composition. Body composition measures can indirectly provide information about fitness status (that is, muscle strength, oxygen uptake). A combination of paralysis and inactivity often leads to an increase in body weight and fat mass, and a decrease in lean tissue mass in people with chronic SCI. This increases the risk of developing secondary health complications and can decrease QoL.

Body weight: Nine studies assessed changes in body weight. All were level 4 or 5 studies. Training protocols included resistance and aerobic exercise,[14,27–29] FES-assisted exercise[30,31] and BWSTT,[32,33] all performed at least 3 × per week. None of the level 4 studies reported significant changes in body weight.

Lean (muscle) and fat body mass: In all, 19 training studies reported changes in lean mass and 7 reported changes in fat mass. All were classified as level 4 or 5, with the exception of one level 2 trial. Training programs involving BWSTT,[32,34,35] FES cycling,[30,31,36–38] FES ambulation,[39,40] neuromuscular electrical stimulation resistance training[41] and vibration exercise[42] produced significant increases in muscle mass, with training frequencies ranging from 2–7 × per week, for 8–52 weeks duration. Of note, the level 2 trial showed significant increases in quadriceps muscle mass after 26 weeks of FES-assisted treadmill training, 2 times per week for 20 min per session.[40] The majority of studies found no significant decreases in fat mass post training. However, in two lower-quality studies (Downs & Black score $\leqslant 12$), significant reductions in fat mass were observed after FES cycling performed 7 × per week for 8 weeks[36] and 5 × per week for 32 weeks.[31]

Functional performance. Measures of functional performance have included tests of wheelchair skills and propulsion, walking and standing. Improvements in these outcomes can translate into increased independence and QoL.

Wheelchair skills and propulsion: These nine studies were all classified as level 4. All showed significant improvements in their respective measures, including time taken to perform selected wheelchair skills, peak power output on a wheelchair ergometer, propulsion speed, distance traveled in 12 min and propulsion time to exhaustion. Training regimens consisted of either arm, wheelchair or rowing ergometry. One study also incorporated stretching and strengthening exercises.[43] Participants exercised 3 × per week in all but one study that prescribed exercise 5 × per week.[44] Sessions ranged from 5 to 45 min. Only one study had a group perform low-intensity exercise.[45] Moderate- to heavy-intensity exercise was prescribed in all other studies.

Walking: Eleven studies reported on treadmill walking parameters (for example, speed, percentage of body-weight support required) and five reported independent, overground walking performance. All studies were level 4, except for one level 1 RCT[46] and a level 5 case study.[32] Significant changes in treadmill walking parameters emerged in most but not all studies, and varied across the parameters measured. Likewise, most studies reported significant improvements in overground walking. In general, there was tremendous variability in training programs across the studies, rendering it impossible to discern training parameters associated with improvements. Training modalities included various types of treadmill training (BWSTT, robotic assisted, manually assisted, FES assisted), FES-assisted overground walking training and lower-body strength training. Training frequency ranged from 2 to 5 sessions per week. Training session duration was participant-determined in some studies and experimenter-determined in others, ranging from 15 to 90 min per session. Of note, the only RCT[46] showed significant improvements in overground walking speed and treadmill training speed across four types of BWSTT prescribed 3 × per week at an individualized intensity.

Standing: A single level 5 case study[32] reported improvements in the participant's ability to stand with a walker following 9 months of progressive BWSTT, performed 3 × per week for an average of 55 min per session.

Discussion

Our systematic review included 13 exercise-training studies involving people with acute SCI and 69 studies involving those with chronic SCI. The review yielded only eight RCTs (five in acute population; three in chronic). Most studies utilized a pre–post study design, with scores $<20/28$ on the Downs & Black evaluation scale. As such, overall, evidence regarding the effects of exercise on fitness is characterized as low quality. Evidence quality is taken into consideration in the following sections addressing our primary research questions: 'Can exercise improve each fitness component?' and, if so, 'What types of exercise improve each component?'

Conclusions from studies of acute SCI

There is insufficient evidence to draw meaningful conclusions regarding the effects of exercise, or specific types of exercise, on any of the four fitness components. It should be noted, however, that a single RCT showed the effectiveness of exercise in improving physical capacity with supporting evidence from four pre–post studies. These encouraging findings require replication in high-quality studies. It is also noteworthy that no study reported fitness decrements. Given the profound deconditioning that follows an SCI, the maintenance and/or absence of significant fitness losses could be interpreted as a positive outcome.

Conclusions from studies of chronic SCI

Based on level 1 and 2 evidence, with consistent and substantial supporting level 4 and 5 evidence, we conclude that exercise training increases physical capacity. This conclusion is consistent with the other two systematic reviews.[2,3] Regarding exercise types, level 1 and 4 evidence showed a combination of resistance and arm ergometry training, performed 2–3 × per week at a moderate intensity (60–80% of max HR, or 60–65% VO_{2peak}), improves physical capacity. In addition, level 2 evidence with consistent and substantial supporting level 4 and 5 evidence showed the effectiveness of 3 × per week FES-assisted exercise. Given the variability across studies, it is impossible to draw conclusions about the relative effectiveness of different types of FES or to recommend a particular intensity. Finally, there is low-quality level 4 and 5 evidence of the effectiveness of wheelchair ergometry and arm ergometry for improving physical capacity. These studies suggest 3 × per week training is effective, but there is insufficient evidence to make conclusions about other aspects of the prescription.

Based on level 1 evidence with consistent, supporting level 4 evidence, we conclude that exercise training increases muscle strength. Level 1 and 4 studies show that a variety of resistance training paradigms are effective, with consistent evidence for the effectiveness of training performed 2–3 × per week, at 50–80% 1 RM. There is also level 1 and level 4 evidence for FES exercise to increase muscle strength. However, the FES protocols are too varied to draw conclusions regarding the specific type or intensity of FES training needed to elicit improvements. Although the data are generally supportive, there is insufficient quantity and quality evidence to draw conclusions regarding the effectiveness or dose of other types of exercise (for example, BWSTT, kayak ergometry) for increasing strength.

There is insufficient evidence to conclude that exercise can affect body composition in people with chronic SCI. Currently, there is no evidence that exercise can decrease body weight. The evidence is mixed regarding the effects of exercise on muscle and fat mass. Although FES-assisted exercise looks very promising for increasing muscle mass and possibly decreasing fat mass, further quality research is needed before conclusions can be drawn regarding its effectiveness.

There is insufficient quality evidence to conclude that exercise improves functional performance. Evidence is mixed regarding the effects of exercise on standing and walking. Some studies showed improvements in overground walking and treadmill training parameters after step training, but there was too much variability across training protocols to draw conclusions about the type, intensity, or frequency of training that elicits improvements. Additionally, there is consistent, albeit low-quality level 4 evidence that ergometry performed 3 × per week at a moderate to heavy intensity can improve wheelchair propulsion. Further quality research on this promising training modality is needed before meaningful conclusions can be drawn regarding its effectiveness.

Summary

Exercise is effective in increasing physical capacity and muscular strength among people with chronic SCI. Although there is insufficient evidence at this time to conclude that exercise has similar fitness benefits for people with acute SCI, there is no evidence to suggest that exercise is harmful to this population. These conclusions, and the exercise protocol information catalogued in Tables 2 and 3, will provide the evidence base for the development of much-needed physical activity guidelines for people with SCI.

Conflict of interest

The authors declare no conflict of interest.

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