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Background. Regular physical activity is important for people with tetraplegia to maintain fitness but may not always be easily integrated into daily life. In many countries, hand cycling has become a serious option for daily mobility in people with tetraplegia. However, little information exists regarding the suitability of this exercise mode for this population.

Objective. The purpose of this study was to evaluate the effects of a structured hand cycle training program in individuals with chronic tetraplegia.

Design. Pretraining and posttraining outcome measurements of physical capacity were compared.

Setting. Structured hand cycle interval training was conducted at home or in a rehabilitation center in the Netherlands.

Participants. Twenty-two patients with tetraplegia (American Spinal Injury Association Impairment Scale classification A-D) at least 2 years since injury participated.

Intervention. The intervention was an 8- to 12-week hand cycle interval training program.

Measures. Primary outcomes of physical capacity were: peak power output (POpeak) and peak oxygen uptake ($\dot{V}O_2$peak), as determined in hand cycle peak exercise tests on a motor-driven treadmill. Secondary outcome measures were: peak muscle strength (force-generating capacity) of the upper extremities (as assessed by handheld dynamometry), respiratory function (forced vital capacity and peak expiratory flow) and participant-reported shoulder pain.

Results. Significant improvements following a mean of 19 (SD=3) sessions of hand cycle training were found in POpeak (from 42.5 W [SD=21.9] to 50.8 W [SD=25.4]), $\dot{V}O_2$peak (from 1.32 L·min^{-1} [SD=0.40] to 1.43 L·min^{-1} [SD=0.43]), and mechanical efficiency, as reflected by a decrease in submaximal oxygen uptake. Except for shoulder abduction strength, no significant effects were found on the secondary outcomes.

Limitations. Common health complications, such as urinary tract infections, bowel problems, and pressure sores, led to dropout and nonadherence.

Conclusion. Patients with tetraplegia were able to improve their physical capacity through regular hand cycle interval training, without participant-reported shoulder-arm pain or discomfort.

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The physical capacity of most people with a cervical spinal cord injury (SCI) is low.[1] In addition to complete or incomplete paralysis, many other factors may contribute to the low physical capacity of this group. People with tetraplegia often have a disturbed sympathetic nervous system that might lead to bradycardia, orthostatic hypotension, autonomic dysreflexia, temperature dysregulation, and sweating disturbances.[2] Depending on the location and severity of the lesion, cardiovascular responses to exercise (eg, increased blood flow to active muscles and vasoconstriction in relatively inactive tissues) may be disturbed.[1,2] Secondary complications such as urinary tract infections, spasms, pressure sores, and overuse injuries in the upper extremity also may lead to inactivity and deconditioning. Other barriers to physical activity may be intrinsic (eg, lack of energy or motivation) or extrinsic (eg, costs, not knowing where to exercise, accessibility of facilities, knowledgeable instructors).[3] Deconditioning eventually may lead to additional health problems such as obesity, diabetes, and cardiovascular problems.[4] Therefore, it is suggested that a certain level of physical activity and fitness is important for people with tetraplegia in order to maintain (or even improve) functioning, participation, health, and quality of life.[5]

In contrast to arm-crank exercise, hand-rim wheelchair propulsion and hand cycling are functional modes of regular daily mobility that are assumed to help people with tetraplegia to maintain a physically active lifestyle. Hand-rim wheelchair propulsion, however, is highly inefficient[6] and mechanically straining, often leading to upper-extremity overuse problems.[7] For people with tetraplegia, it may even be difficult to apply a well-directed force during every push.[8] For them, hand cycling may be easier to perform than hand-rim wheelchair propulsion. The hands are fixed in pedals with special grips, and forces can be applied continuously over the full 360-degree cycle in both push and pull phases. In contrast, during hand-rim wheelchair propulsion, force can be applied in only 20% to 40% of the cycle.[6] Furthermore, Dallmeijer et al[9] found a higher mechanical efficiency and peak power output (POpeak) in hand cycling compared with hand-rim wheelchair propulsion. According to clinical experience, people for whom hand-rim wheelchair propulsion is too strenuous appear to be able to hand cycle a few hundred meters after only a few practice sessions.

Only a few intervention studies are available on the effects of upper-body training in people with tetraplegia.[10] These studies were performed with different modes of arm exercise: arm cranking,[11,12] wheelchair propulsion,[13] circuit resistance training,[14] or quad rugby.[15] The ergonomics of arm cranking in these studies[11,12] differed substantially from the ergonomics of hand cycling in the current study (ie, asynchronous arm cranking versus synchronous hand cycling). A high position of the crank axis (midpoint of the sternum[11] or at shoulder level[12]) is used in arm cranking versus the low position (just below the sternum) used in hand cycling.

Training studies on the effects of hand cycling in people with SCI are even scarcer, with only one study in people with paraplegia[16] and no studies in people with tetraplegia. In a recent observational study on the influence of hand cycling during and 1 year after clinical rehabilitation, we found clinically relevant improvements in physical capacity in patients with paraplegia during rehabilitation, but not in patients with tetraplegia, probably due to the small and heterogeneous groups.[17]

The aim of this study was to evaluate the effects of a structured hand cycle interval training intervention on physical capacity in people with tetraplegia at least 2 years postinjury. We hypothesized that a structured hand cycle training intervention significantly improves physical work capacity.

Method

Participants

People with cervical SCI who had been rehabilitated in 1 of 3 Dutch rehabilitation centers were approached to participate. Participants were included if they: (1) had been discharged from clinical rehabilitation more than 1 year previously and had a time since injury (TSI) of at least 2 years, (2) had a motor incomplete C5–C8 lesion (American Spinal Injury Association Impairment Scale [AIS] classification A–D),[18] (3) used a manual or powered wheelchair for mobility, (4) were physically active in training and outdoor mobility less than 2 hours a week over the past 3 months, (5) were between 18 and 65 years of age, and (6) had sufficient knowledge of the Dutch language. A physician medically screened all participants. Exclusion criteria were: severe overuse injuries of the upper extremities screened with a questionnaire,[19] other secondary health problems (ie, pressure sores, bladder infections, cardiovascular diseases, or contraindications for exercise according to American College of Sports Medicine guidelines[20]), or other medical conditions that did not allow performance of physical activities. All participants signed an informed consent form.

Design

The pretraining-posttraining design involved a pretraining test (t1), performed 1 week before the start of the 8- to 12-week training period, and a posttraining test (t2), performed 1 week after the end of the training period. A subgroup performed an extra test (t0) prior to t1, and the second baseline measurements (t1) were taken for analysis to rule out the effects of practicing.

Peak power output and peak oxygen uptake ($\dot{V}O_2$peak) during the hand cycle peak exercise test were the primary outcome measures of physical capacity. Muscle strength (force-generating capacity) and pulmonary function were evaluated as secondary outcome measures.

Intervention: Hand Cycling

The add-on hand cycle. The participants used an add-on hand cycle system* (equipped with bullhorn-shaped cranks and a front wheel) that was coupled to the front of the regular everyday hand-rim wheelchair. The crank pedals move synchronously with alternating flexion and extension of the arms during the 360-degree cycle (Figure). In contrast to conventional straight cranks, the wide bullhorn cranks allow positioning of the crank axis as low as possible, slightly above the upper legs, and, consequently, allow the pedals to move alongside the upper legs (in the lowest position). The hand cycle is equipped with gears that can be changed manually or by moving the chin forward or backward along the switches.

* Double Performance, Antwerpseweg 13-1, Gouda, the Netherlands.

Figure.
Add-on hand cycle system.

Training protocol. Because not all participants in the study were acquainted with hand cycling, 1 practice session a week was conducted in the 3 weeks before the test. For all participants, we aimed at a total of 24 training sessions within a continuous period of 8 to 12 weeks. Those participants who were using a hand-rim wheelchair as their primary mode of mobility were assumed to be able to maintain a frequency of 3 training sessions a week for 8 weeks. Those who used an electrical wheelchair were advised to train twice a week for 12 weeks. At least 1 day of rest was scheduled between training days. All participants were asked to continue their regular physical activities and to make up for any missed training session. Depending on their personal situation, participants had the opportunity to train in the rehabilitation center or at home and both indoors and outdoors. To ensure training in case of bad weather conditions, participants received indoor bicycle roller trainers† that were adjusted for hand cycling. The duration of one training session was between 35 and 45 minutes (Appendix). During training, participants wore heart rate (HR) monitors and were expected to train at 60% to 80% of heart rate reserve (HRR) (peak heart rate [HRpeak] − resting heart rate [HRrest] [bpm]).[21] Rating of perceived exertion (RPE) was monitored using the Borg 10-point scale and was intended to range from 4 to 7, starting at the lower level in the first training sessions.[22] Participants were asked to keep a training diary and to score upper-extremity pain following a standardized protocol.[19] Data from the HR monitors during the training period were saved for further analysis. If serious complaints of upper-extremity pain or illness occurred, the participants were asked to contact the trainer/researcher before continuation of the training.

† Minoura Magturbo, 1197-1 Godo, Anpachi, Gifu, 503-2305, Japan.

Outcome Measures

Physical capacity. Prior to testing, participants were asked to empty their bladder to help prevent possible bouts of autonomic dysreflexia. Resting heart rate and resting oxygen uptake ($\dot{V}O_2$rest) were monitored during 5 minutes of quiet sitting. Subsequently, participants were familiarized with the hand cycle on the treadmill,‡ and the experimental velocity was adjusted to the ability of the participant, but within the range of 1.11 to 1.94 $m \cdot s^{-1}$ and a gear setting resulting in a cadence of approximately 60 rpm. Mean submaximal oxygen uptake ($\dot{V}O_2$submax) and submaximal heart rate (HRsubmax) were measured at a constant load in the last 30 seconds of a 3-minute submaximal hand cycle bout. Because velocity and gear setting were kept the same during all measurement occasions, submaximal power output (POsubmax) was comparable between measurements, and a lower $\dot{V}O_2$submax would indicate increased mechanical efficiency.

After 3 minutes of rest, POpeak (W), $\dot{V}O_2$peak ($mL \cdot min^{-1}$), and HRpeak (bpm) were determined in a discontinuous graded peak exercise test performed in the hand cycle on a motor-driven treadmill. Exercise bouts of 2 minutes were interspaced with a rest period of 30 seconds. After each exercise step, the workload was increased by adding resistance (F_{add}).[9] Increments of 2.00 to 5.25 W were imposed until exhaustion. The test protocol was previously described by Valent et al.[21] Rolling resistance (F_{rol}) of the individual hand cycle-user combination on the treadmill was determined in a drag test on the treadmill.[23] The power output (PO) was calculated from the separately measured individual drag force (F_{rol} [N]), F_{add} (N), and treadmill belt velocity (v [$m \cdot s^{-1}$]):

$$PO(W) = (F_{rol} + F_{add}) \times v$$

During the test, oxygen uptake ($\dot{V}O_2$) was measured continuously with an Oxycon Delta spirometer.§ The highest average 30-second values of PO and $\dot{V}O_2$ during the test were defined as POpeak and $\dot{V}O_2$peak. Heart rate was continuously monitored with an HR monitor,‖ and HRpeak was defined as the highest HR value recorded in a 5-second interval. Cardiovascular efficiency, reflected by the oxygen pulse (O_2P [$mL \cdot beat^{-1}$]), was calculated from $\dot{V}O_2$peak and HRpeak (O_2P [$mL \cdot beat^{-1}$] = $\dot{V}O_2$peak [$mL \cdot min^{-1}$]/HRpeak [bpm]).[24]

Muscle strength. Arm muscle groups (elbow flexors and extensors, shoulder exorotators and endorotators, and abductors) that scored ≥3 on manual muscle testing were tested with handheld dynamometry (Microfet#), according to a standardized protocol.[25] A break test was performed in which the participants built up a peak force against a dynamometer, after which the examiner applied a sufficiently higher resistance to break through it.[26] The peak forces of the left- and right-side muscle groups were summed. Only data of participants with a strength score for both left and right sides for a certain muscle group were included in the strength analysis.

Pulmonary function. To assess training effects on pulmonary function, we measured and analyzed simple spirometric values with the Oxycon Delta spirometer. Forced vital capacity ($mL \cdot min^{-1}$) and peak expiratory flow ($mL \cdot min^{-1}$) were recorded relative to age-, sex-, and body weight-corrected normative data.

Adverse Effects

Pain in the upper extremities (ie, the musculoskeletal system) was scored before and after the training period with a self-designed questionnaire on a 5-point scale (1=not serious, 5=very serious).[19] We scored shoulders, elbows, and wrists separately, but the scores for left and right sides were summed.

Data Analysis

The change between the pretraining and posttraining outcome measurements was examined using SPSS version 15** with a paired, 2-tailed Student *t* test ($P<.05$).

Results

Twenty-two participants were included in this training study (Tab. 1). Five participants were moderately active (1.5 hours a week), and all other participants were minimally physically active or were not physically active. Fifteen participants completed the training period (t1–t2) and performed a pretest and a posttest. A subgroup (participants 1–7) of these 15 participants also performed an extra test (t0).

Seven participants dropped out during the training period due to various reasons: problems with transportation to the training facility (participant 18), a chronic urinary tract infection (participant 19), persistent bowel problems combined with spasms (participant 20), pressure ulcers as a consequence of a fall out of the wheelchair at home (participant 21), a work-related overuse injury of the elbow (participant 22), serious pain as a consequence of bowel problems (participant 17), and illness (the flu) after 3 weeks of training (participant 8).

No significant differences were found in personal and lesion characteristics among the 7 participants who dropped out (Tab. 1) and those who completed the training (n=15): age ($\bar{X}$=43 years, SD=13 versus $\bar{X}$=38 years, SD=11); TSI ($\bar{X}$=9

‡ Bonte Techniek BV, Amperestraat 25A 8013 PT, Zwolle, the Netherlands.

§ Viasys-HC, De Molen 8/10, 3994 DB, Houten, the Netherlands.

‖ Polar Electro Nederland BV, Postbus 1044, 1300 BA Almere, the Netherlands.

Biometrics Europe BV, Kabelstraat 11, 1322 AD Almere, the Netherlands.

** SPSS Inc, 233 S Wacker Dr, Chicago, IL 60606

Table 1.
Participant Characteristics, Training Adherence, and Peak Power Output (POpeak) and Peak Oxygen Uptake ($\dot{V}O_2$peak) Measurements[a]

Subject No.	Sex	Age (y)	TSI (y)	Weight (kg)	Lesion Level (Right/Left)	AIS Classification	Daily Wheelchair	ISPS (0–3)	Phys Act (hr/wk)	Hand Cycle Experience	Training Period (wk)	Sessions Completed	POpeak (W)		$\dot{V}O_2$peak ($L \cdot min^{-1}$)	
													Pre	Post	Pre	Post
1	M	41	15	83	C6/C6	B	El	0	0	No	10	17	28.8	38.8	1.12	1.38
2	M	22	2	86	C6/C7	B	Hr	0	1.5	Yes	8	24	51.8	65.0	1.60	1.93
3	M	37	15	85	C6/C6	B	Hr	0	1.5	Yes	8	23	74.3	78.5	1.60	2.02
4	F	31	17	58	C6/C7	C	Hr	3	1	Yes	8	23	41.8	53.8	1.21	1.57
5	F	37	20	65	C6/C6	D	El	3	0	No	8	20	14	16	0.95	0.95
6	M	64	3	88	C7/C7	B	El	1	0	Yes	10	20	24	28	0.91	0.84
7	M	29	7	70	C6/C6	B	Hr	0	1	Yes	8	24	41.9	52.4	1.10	1.15
8	M	42	3	117	C6/C6	A	El	3	0	Yes	3	do	32.0		0.82	
9	M	54	28	81	C7/C7	B	Hr	0	1.5	Yes	8	24	69.6	74.2	2.20	2.00
10	M	32	6	77	C7/C7	B	Hr	1	1.5	Yes	8	19	66.8	82.7	1.50	1.72
11	M	43	8	113	C5/C5	A	El	2	1.5	Yes	6	13	16.0	16.0	0.91	1.04
12	M	32	12	80	C7/C8	A	Hr	0	1	Yes	7	18	66.6	86.0	1.73	1.87
13	M	28	6	84	C8/C8	B	Hr	0	1	Yes	8	19	60.6	71.7	1.40	1.66
14	M	44	2	71	C8/C8	D	Hr	0	0	Yes	7	17	47.1	57.6	1.69	1.39
15	F	48	6	70	C5/C7	B	Both	2	1	Yes	12	24	20.6	21.0	1.08	1.12
16	M	25	3	63	C5/C5	A	El	0	0.5	Yes	8	20	14.0	22.0	0.75	0.81
17	M	48	12	100	C5/C6	B	Hr	2	0.5	No	0	do	32.0		1.12	
18	F	58	20	84	C6/C6	B	El	1	0	No	5	do	23.7		0.94	
19	M	45	2	64	C8/T1	B	Hr	1	0	No	4	do	28		0.80	
20	M	34	3	77	C7/C7	B	Hr	0	1	Yes	3	do	36		1.32	
21	M	21	6	60	C5/C6	A	El	0	0.5	Yes	10	do	16		0.61	
22	M	51	16	110	C6/T1	A	Hr	1	0	Yes	1	do	17.8		0.90	
$\overline{X}$		39	10	81							8	19	42.5	50.9	1.32	1.43
SD		12	7	17							1	3	21.9	25.4	0.40	0.43

[a] M=male, F=female, TSI=time since injury, AIS=American Spinal Injury Association Impairment Scale,[18] Hr=hand-rim wheelchair, El=electric wheelchair, ISPS=initial shoulder pain score (1=minimal pain, 2=slightly moderate pain, 3=moderate pain), Phys Act=physical activity (sports or outdoor manual wheelchair propulsion), do=dropout, pre=pretraining, post=posttraining.

years, SD=7 versus $\bar{X}$=10 years, SD=8), body mass ($\bar{X}$=87.4 kg, SD=22.2 versus $\bar{X}$=78.2 kg, SD=13.3), lesion level (C5 [n=2], C6 [n=3], C7 [n=1], and C8 [n=1] versus C5 [n=3], C6 [n=6], C7 [n=4], and C8 [n=2]), and AIS classification[18] (A [n=3], B [n=4], C [n=0], and D [n=0]) versus A [n=3], B [n=9], C [n=1], and D [n=1]), respectively. However, the dropouts had significantly lower baseline levels of the primary outcome measures of physical capacity than those who completed the study: POpeak ($\bar{X}$=26.5 W, SD=7.2 versus $\bar{X}$=42.5 W, SD=21.9) (P=.099) and $\dot{V}O_2$peak ($\bar{X}$=0.93 L·min^{-1}, SD=0.25 versus $\bar{X}$=1.32 L·min^{-1}, SD=0.40) (P=.04), respectively.

Five dropouts had light to moderate shoulder pain at baseline. Six participants who completed the training period initially had light to moderate shoulder pain, and 4 of these participants appeared to have a low baseline physical capacity and only slight absolute improvements after training (Tab. 1).

Training

Protocol. It turned out to be difficult for the participants to complete 24 training sessions within the designated period (Tab. 1). Five participants missed 5 to 7 sessions, which was more than 20% of all sessions. The main reasons reported were: not feeling well because of an illness (urinary tract infection, flu), transportation problems, too busy (with work), too tired, and no people available to help start up training. Overuse injuries were not mentioned.

The distances covered during the hand cycle training sessions increased over time and varied from 2 to 7 km. All participants who completed the training managed to train at, on average, 60% to 80% of HRR, with the 1- to 2-minute rest intervals included. During the 3- to 4-minute hand cycle intervals, the HR was between 70% and 80% of HRR. A mean intensity of 6 (SD=1) on the 10-point Borg scale was reported after the training sessions, compared with 7 (SD=2) after completing the peak exercise test. Particularly those participants with a very limited active muscle mass and a high body mass, who already were exerting at a near-maximal level when moving the hand cycle forward, initially had to hand cycle in a roller trainer (at a lower power level). After 4 to 6 weeks of training, all participants who completed the training were able to train outdoors at the suggested intensity.

Adverse effects. The training was never stopped because of complaints of pain in the arms or shoulders, although 3 participants were advised on one occasion to postpone the next training day or to train at a lower intensity (or gear setting). Comparing pretraining and posttraining pain scores, no increase in pain scores for the wrists or elbows was found following hand cycle training. Three participants (participants 3, 6, and 11) reported a slightly higher shoulder pain score after training compared with before training. All 3 participants mentioned that this higher pain score was due to muscle soreness as a consequence of training too hard (with a gear setting that was too high), which disappeared within 1 day after training.

Outcome Measures

Hand cycle capacity. Table 2 presents the results of the pretest-posttest design (n=15). Mean peak respiratory exchange ratio was 1.10 in both the pretest and the posttest, suggesting that, in general, $\dot{V}O_2$peak was reached. The $\dot{V}O_2$peak significantly improved, on average, 114 mL·min^{-1} (SD=204) after training, which was an increase of 8.7% (SD=13.9%). In addition, a significant improvement in POpeak of 8.3 W (SD=5.8) was found after training, which was an increase of 20.2% (SD=15.0%).

No significant improvement in O_2P (mean difference=1.3 mL·beat^{-1}, SD=0.2) (P=.06) was seen in the pretraining-posttraining comparison (n=14; Tab. 2). As expected, HRpeak (n=14) did not change between pretraining ($\bar{X}$=128 b·min^{-1}, SD=24) and posttraining (127 b·min^{-1}, SD=27). A significant decrease in $\dot{V}O_2$submax during hand cycling of 73 mL·min^{-1} (SD=122) ($\bar{X}$=8.8%, SD=14.6%) (P=.04) was found (n=14; Tab. 2) at a constant power output, indicating improved gross mechanical efficiency during hand cycling.

Secondary outcomes. Only shoulder abduction strength significantly improved ($\bar{X}$=5.6%, SD=11%; Tab. 2). No effects of hand cycle training were found on pulmonary function outcome measures.

Discussion

Structured hand cycle interval training showed significant positive effects on the primary outcomes of physical capacity (POpeak and $\dot{V}O_2$peak) but not on the secondary outcomes (muscle strength and pulmonary function).

Training

A relatively high dropout rate of approximately 30% was encountered in the training period. The relatively low baseline physical capacity in the dropouts compared with participants who completed the training period may have been a result of a long history of health problems that prevented them from maintaining their fitness level. In general, initial shoulder pain was more prevalent in the study dropouts. Furthermore, people with a relatively low physical capacity may be in a vulnerable health condition and thus more

Table 2.
Results of Hand Cycle Training: Paired *t*-Test Analysis of Outcome Measures Pretraining (t1) and Posttraining (t2) (n=15)[a]

Physical Capacity	n	t1	t2	Difference (t2 − t1)	
		$\bar{X}$ (SD)	$\bar{X}$ (SD)	*P*	$\bar{X}$ (95% CI)
Hand cycle capacity					
POpeak (W)	15	42.5 (21.9)	50.8 (25.4)	<.001	8.3 (5.2 to 11.5)
$\dot{V}O_2$peak (mL·min^{-1})	15	1,317 (399)	1,431 (427)	.05	114 (0 to 227)
$\dot{V}O_2$peak (mL·kg^{-1}·min^{-1})	14	17.3 (5.2)	19.1 (5.7)	.03	1.8 (0.2 to 3.4)
O_2Ppeak (mL·beat^{-1})	14	10.7 (2.8)	12.0 (4.0)	.06	1.3 (0.1 to 2.5)
VEpeak (L·min^{-1})	15	52.0 (17.3)	54.9 (19.2)	.15	2.9 (−1.9 to 7.0)
RERpeak	15	1.10 (0.16)	1.10 (0.14)	.93	0.01 (−0.03 to 0.07)
$\dot{V}O_2$submax (mL·min^{-1})	14	834 (116)	761 (58)	.04	−73 (−144 to −3)
HRsubmax (bpm)	14	92 (17)	88 (18)	.40	−4 (−13 to 5)
Muscle strength (HHD)					
Extension (L+R) (N)	8	331 (99)	321 (96)	.47	−10 (−42 to 21)
Flexion (L+R) (N)	15	571 (176)	578 (177)	.49	7 (−14 to 27)
Endorotation (L+R) (N)	12	358 (130)	360 (118)	.83	2 (−9 to 19)
Exorotation (L+R) (N)	12	294 (101)	304 (98)	.10	10 (−2 to 22)
Abduction (L+R) (N)	15	336 (86)	355 (80)	.05	19 (0 to 38)
Pulmonary function					
FVC (L·min^{-1})	15	3.80 (1.24)	3.82 (1.21)	.80	−0.02 (−0.21 to 0.16)
FVC (%)	15	75.5 (15.4)	76.8 (17)	.45	1.2 (−2.1 to 4.7)
PEF (L·min^{-1})	15	6.52 (2.23)	6.14 (2.00)	.07	−0.37 (−0.78 to 0.04)
PEF (%)	15	70.0 (21.3)	66,3 (18.9)	.27	−3.7 (−8.2 to 0.8)

[a] CI=confidence interval, POpeak=peak power output, $\dot{V}O_2$peak=peak oxygen uptake, O_2P=peak oxygen pulse, $\dot{V}O_2$submax=submaximal oxygen uptake, HRsubmax=submaximal heart rate, HRrest=resting heart rate, $\dot{V}O_2$rest=resting oxygen uptake, RER=respiratory exchange ratio, VEpeak=peak ventilation, HHD=handheld dynamometry, L=left, R=right, FVC=force vital capacity, PEF=peak expiratory flow. For some outcome measures of hand cycle capacity, data were missing in one (but not the same) participant due to measurement errors. Muscle strength was not available for all muscle groups (as the participants scored less than 3 on manual muscle testing or manual muscle testing was not feasible due to pain).

prone to developing health problems. On the other hand, health problems, although less severe, also were responsible for the high nonadherence rate found in the participants in the training program. It should be noted that health problems in both dropouts and participants who completed training were not related to the training. It can be concluded that untrained people with tetraplegia are in a vulnerable health condition[27] and that health problems are likely to interfere with their life and thus with their ability to perform training programs.

Protocol. From a preceding unpublished pilot project in untrained subjects with tetraplegia, interval training appeared to be more suitable than continuous aerobic training. Most of the participants in our pilot project were not able to hand cycle continuously for longer than approximately 5 to 7 minutes, whereas several hand cycle blocks of 3 minutes, with rest intervals between blocks, were easily sustainable and without extreme muscle fatigue. Therefore, a hand cycle interval training (and discontinuous test) protocol was designed. The exercise intensity was within the range of 50% to 90% HRR, HRpeak, and POpeak, which was imposed in previous upper-body training studies in people with tetraplegia.[10] The broad range in RPE scores (4–7) as well as HRR values (60%–80%) accounted for the variation in intensity common during interval training.[28]

It should be noted from a previous study[21] that HRR and RPE scores have limitations for monitoring exercise intensity in people with tetraplegia. The study participants tended to score local arm muscle fatigue instead of overall perceived exertion, which is intended by the Borg scale.[21] In addition, HR may not always reflect exercise intensity adequately, probably due to a disturbed sympathetic innervation (ie, of the heart, resulting in a low HRpeak[29]) or other factors related to the low physical capacity and muscle mass involved.[21]

Despite these limitations, however, RPE together with HRR appeared reasonably useful in training people with tetraplegia. The 2 methods combined helped participants to know their body responses to exercise and understand that HR may not always reflect exercise intensity. For example, study participants reported higher-than-normal HR values (and better performance) during training in the days before a bladder infection or illness was diagnosed. This finding suggests that symptoms of autonomic dysreflexia were present.

Adverse effects. In about 40% of the participants, light to moderate pain to the upper extremities was already present before they were included in the present study. With a prevalence between 40% and 70%,[7,19] pain in the upper extremities, especially in the shoulder, is common in people with tetraplegia. They are at higher risk for developing musculoskeletal pain as a consequence of partial paralysis of thoracohumeral muscles and imbalance in shoulder muscles.[7]

We noticed that 2 out of 3 participants with temporal shoulder complaints (participants 2 and 3) were the only individuals who were using conventional straight cranks (with a high-positioned crank axis). They were forced to move their arms further against gravity and even above shoulder level, which may be disadvantageous for the shoulder musculature.

Despite instructions, participants tended to cycle with higher resistance instead of higher pedal frequencies. Cycling at a high resistance potentially can overload the musculoskeletal system, but is not reflected by exercise intensity (HRR). Therefore, especially in the first weeks of training, supervision of the training regimen is recommended. Moreover, for those individuals with initial shoulder pain, it is advised to incorporate an additional muscle (rotator cuff) strengthening program into the training protocol.[30]

Outcome Measures

Hand cycle capacity. The primary outcome measures in the study, POpeak and $\dot{V}O_2$peak, showed significant improvements over the training period. Table 1 shows the large interindividual differences in our main outcomes, and clearly an improvement of 8 W after training is more substantial for someone with a baseline value of 16 W than for someone with a baseline value of 60 W. Moreover, it is difficult to compare absolute gains in POpeak and $\dot{V}O_2$peak with the literature when different test devices and protocols have been used and with subjects with different training statuses.[10] Nevertheless, the relative gains of 20.2% in POpeak and 8.7% in $\dot{V}O_2$peak in the present study were in agreement with the study by McLean and Skinner,[11] who found gains of 13.7% and 8.3%, respectively, after arm crank exercise. In another study on arm crank exercise in young people with tetraplegia, gains of 23.8% in POpeak and 99% in $\dot{V}O_2$peak were found.[12] Dallmeijer et al[15] did not find any significant improvements in POpeak or $\dot{V}O_2$peak after quad rugby training (once a week). During clinical rehabilitation, Hjeltnes and Wallberg-Henriksson[31] found significant gains in POpeak but no improvements in $\dot{V}O_2$peak.

The question remains: How much improvement is clinically relevant? According to Brehm et al,[32] 10% is considered to be a meaningful change. Applying this arbitrary cutoff in the current study, an improvement in POpeak is designated clinically relevant and the change in $\dot{V}O_2$peak is nearly clinically relevant. The gains in work capacity indicate the ability to improve fitness in people with tetraplegia. The effects of hand cycle training probably will be primarily local and not necessarily central, given the extremely low muscle mass that is actively involved in the exercise in this population.[1] The greater relative increase in POpeak (20.2%) compared with $\dot{V}O_2$peak (8.7%) and the decrease in $\dot{V}O_2$submax indicate an improvement in gross mechanical efficiency[33] (ie, effects in reduced co-contraction as part of muscle coordination of the arms and shoulders, as well as in external force production). Another possible explanation may be an improved exercise tolerance in the muscles.

Muscle strength. No clinically relevant improvements in muscle strength were found after hand cycling. In general, however, the participants reported feeling stronger. A possible explanation may be improved exercise tolerance in the muscles. This improved exercise tolerance likely results from changes in muscle metabolism (eg, increase in mitochondria, improved glycogen storage and synthesis) or a higher density of capillaries, during which less lactic acid is accumulated and diminished muscle fatigue is experienced.[34] In the current study, however, we measured isometric peak strength and not muscle endurance.

Pulmonary function. No improvements in functional vital capacity or peak expiratory flow were found. In the literature, however, it appears that the effects of upper-body training on pulmonary function in people with high levels of paraplegia or tetraplegia are not uniform.[10,35,36]

Study Limitations

The optimal study design (ie, a randomized controlled trial) was not feasible due to the small number of available participants. Another limitation was the variability in baseline physical capacity among the participants. However, coalescing subgroups to reduce variability was hampered by the small sample size. The number of dropouts and the nonadherence rate were considerable, but not uncommon in training studies in people with tetraplegia.[10] Due to dropouts, the group serving as their own controls (n=7) was too small to perform statistical analysis of a double baseline group. With 19 training sessions (instead of 24), our participants trained less than planned. Nevertheless, a positive effect was found on physical capacity.

Conclusions and Recommendations

A successful integration of aerobic exercise training into the daily life of people with tetraplegia may be more likely if aerobic exercise is safe, easily adjustable to a person's low physical capacity, fun to do, motivating, low key, and useful in daily mobility, as well as encouraging social participation. Hand cycling may meet these requirements. Important are an adequate ergonomic interface and an optimal range of gear ratios (or initial use of roller trainers) to impose an adequate power output. Hand cycling around wherever you like and over meaningful distances may be fun to do. After a training period, it may be motivating to see improvements in fitness level and distances covered. Hand cycling (with an attachable unit) may be low key, as no transfers have to be made, and certainly if someone can start from home. The hand cycle may be useful for daily mobility in an ergonomically suitable environment. Hand cycling with peers or together with family members and friends during activities such as walking, jogging, or skating may encourage social participation. Especially vulnerable individuals with a low physical capacity can benefit from initial supervision by skilled professionals who can help them overcome personal and practical barriers in daily life. Future research should focus on the optimization of hand cycle training protocols (eg, training at a certain percentage of the POpeak, in watts, which was derived from the exercise test[21,37]) specifically designed for people with tetraplegia.

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Appendix.

Training Protocol (12 Weeks)

Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12
3 min hc[a]	3 min hc	3 min hc	3 min hc	3 min hc	3 min hc	3 min hc	4 min hc	4 min hc	4 min hc	4 min hc	4 min hc
2 min rest	2 min rest	1.5 min rest	1.5 min rest	1.5 min rest	1 min rest	1 min rest	1.5 min rest	1.5 min rest	1 min rest	1 min rest	1 min rest
6×	7×	7×	8×	8×	8×	8×	7×	7×	7×	7×	8×

[a] hc=hand cycling.