

Original Article

The individual relationship between heart rate and oxygen uptake in people with a tetraplegia during exercise

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Study design: Descriptive study.

Objective: To examine the individual heart rate–oxygen uptake (HR– $\dot{V}O_2$) relationship during exercise in persons with tetraplegia (TP).

Setting: Rehabilitation Centre Heliomare, Wijk aan Zee, The Netherlands.

Methods: The HR– $\dot{V}O_2$ relationship was determined in untrained subjects with motor complete TP (C5 or C6, $n = 10$ and C7 or C8, $n = 10$) during a discontinuous graded exercise hand cycle test. The mean HR and $\dot{V}O_2$ of the final 60 s of 2-min exercise blocks were used for calculation of the individual correlation coefficient and the standard error of the estimate (SEE).

Results: Two subjects of the C5–C6 group were not able to complete the test. Individual Pearson's correlation coefficients (r) ranged from 0.68 to 0.97 and SEE from 2.6 to 22.4% $\dot{V}O_{2R}$ Reserve ($\dot{V}O_{2R}$). The mean Pearson's r and SEE were 0.81 ± 0.12 and $10.6 \pm 5.6\%$ $\dot{V}O_{2R}$ in the C5–C6 group and 0.91 ± 0.07 and $7.0 \pm 3.2\%$ $\dot{V}O_{2R}$ in the C7–C8 group, respectively. Two subjects of the C5–C6 group and six subjects of the C7–C8 group attained a linear HR– $\dot{V}O_2$ relationship with an acceptable SEE ($\leq 6.0\%$) and $r (> 0.90)$.

Conclusions: The HR– $\dot{V}O_2$ relationship appeared linear in only eight out of 18 subjects. An individual analysis of the HR– $\dot{V}O_2$ relationship is necessary to determine whether HR can be used to quantify exercise intensity. The use of HR to prescribe training intensity should be reconsidered in persons with TP.

Sponsorship: This study is supported from a grant by ZON-MW.

Spinal Cord (2007) 45, 104–111. doi:10.1038/sj.sc.3101946; published online 27 June 2006

Keywords: tetraplegia; heart rate; oxygen uptake; hand cycling; training intensity

Introduction

In able-bodied persons, heart rate (HR) and oxygen uptake ($\dot{V}O_2$) are linearly related and therefore exercise training intensity can be prescribed, based on HR. This is an advantage because the measurement of $\dot{V}O_2$ during training is complicated, whereas HR can be easily recorded. In persons with a spinal cord injury (SCI), HR has also been used to prescribe training intensity,¹ as well as to indicate physical strain in daily activities.^{2–4} The guidelines of the American College of Sports Medicine (ACSM) for training of able-bodied persons – 50–85% heart rate reserve (HRR)⁵ – have also been applied in training studies with persons with paraplegia (PP)⁶ as well as tetraplegia (TP).^{7,8} These guidelines may

be valid for persons with PP, as several studies^{9–14} showed a strong individual linear HR– $\dot{V}O_2$ relationship in persons with PP. In individuals with TP however, this may be different as a result of the disturbed sympathetic innervation, which may affect the HR– $\dot{V}O_2$ relationship.

The sympathetic innervation of the heart derives from Th1 to Th4 and therefore spinal cord lesions at or above Th4 may lead to inappropriate cardioacceleration.¹⁵ The increase in HR during exercise in these persons is mostly due to withdrawal of vagal parasympathetic stimulation.¹⁶ As a consequence, maximal HR in individuals with TP is often restricted to about 130 beats per minute (b.p.m.).¹ Moreover, normal cardiovascular responses to exercise (eg vasoconstriction in relatively inactive tissues and increased blood flow to active muscle) are diminished as a consequence of the disturbed sympa-

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thetic nervous system.¹⁵ In a study of Hjeltnes *et al*¹⁷ in persons with TP, it was indeed shown that, compared to able-bodied, mean blood pressure (BP) and oxygen tension (PO_2) in arterial blood were reduced during graded exercise. Furthermore, as a consequence of the disturbed sympathetic innervation, autonomic dysreflexia (AD) may occur in subjects with a lesion level at or above Th6.¹⁸ AD may result in an uncontrolled elevation of BP, and during exercise, this may lead to sudden changes in HR and eventually a higher HR_{peak} and VO_{2peak} .¹⁹

Apart from the disturbed sympathetic innervation, persons with TP have a low physical capacity as a consequence of the low active muscle mass and inactivity of the venous muscle pump. Because of the disturbed sympathetic innervation and the low physical capacity, it is questionable whether HR can be used for monitoring exercise intensity in persons with a high-level PP or TP.

When looking more closely at studies investigating the HR- VO_2 relationship in persons with PP, hardly any subjects with a complete Th1-Th4 lesion – with possibly disturbed sympathetic innervation of the heart – were included.^{9,10,12,14} Moreover, only a few studies have focused on the HR- VO_2 relationship in persons with TP^{13,20,21} and only one focused on the individual relationship.²⁰ The available studies all use hand rim wheelchair or arm crank exercise to investigate the HR- VO_2 relationship.

In the last decade, hand cycling (Figure 1) has become a very popular alternative for daily outdoor wheelchair use in the Netherlands, also among persons with TP. These systems were found to be more efficient and less straining than hand rim wheelchair propulsion^{22,23} and can be used also in early rehabilitation and in fragile individuals. Moreover, it seems possible to attain significantly higher peak VO_2 , power output (PO) and HR-values in hand cycling compared to wheelchair propulsion.²² Therefore, hand cycling seems to be very appropriate for training and testing of persons with TP.



Figure 1 Example of a hand cycle with attach unit

The aim of this study is to examine the individual HR- VO_2 relationship in individuals with TP to answer the question: Can HR be used to quantify exercise intensity in persons with TP during hand cycling?

Methods

Subjects

Twenty subjects (with TP), aged between 21 and 64 years participated in this study. Ten subjects were classified as having a high-level cervical lesion (C5 or C6) and 10 were classified as having a low-level cervical lesion (C7 or C8) (Table 1). All subjects had motor complete lesions, classified on the American Spinal Injury Association (ASIA) impairment scale²⁴ as A or B. Seven subjects of the high lesion group and one subject of the low lesion group used an electric-powered wheelchair. The other subjects all used manual wheelchairs. All participants were considered to be untrained to moderately trained (no more than 2 h of sport participation weekly during the last 3 months). Four subjects were not experienced in hand cycling at all (Table 1). Before testing, all participants were medically screened by a physician. Exclusion criteria were: Serious overuse injuries of the upper extremities or other impairments, which do not allow performing physical activity (pressure sores), bladder infection and other medical conditions, use of β -blockers and cardiovascular diseases. The subjects were closely monitored on symptoms of AD before and during the execution of the test. Symptoms of AD^{18,25} are extreme hypertension, abnormal high or low HR. Above lesion level: pounding headache, initially pallor, flushed skin, excessive sweating, nasal stuffiness and anxiety. Below lesion level: pallor, goose bumps and cold skin. If any of the symptoms would occur, the test was terminated and not included in the analysis. Approval was obtained from the Medical Ethics Committee of the VU University Medical Center in Amsterdam and all subjects signed an informed consent form. Subject 7, 15 and 16 were in the final stage of the clinical rehabilitation and the other subjects were measured after rehabilitation.

Design and protocol

To determine the individual relationship between HR and VO_2 , subjects with TP performed a standardised discontinuous graded exercise hand cycle test on a motor-driven treadmill. The medical examination before the test included ASIA scoring, BP measurement and medication use. Before subjects started the test, they were asked to empty their bladder to prevent the occurrence of symptoms of AD. Oxygen uptake (VO_2 , l/min), carbon dioxide output (VCO_2 , l/min) and ventilation (V_e , l/min) were continuously measured using a computerised breath-by-breath gas analysing system (Oxycon Delta, Viasys, Bilthoven, The Netherlands). HR (b.p.m.) was recorded with a HR monitor (Polar Sport tester, Polar Electro Inc., Kempele, Finland). Before the graded exercise hand cycle test, resting

Table 1 Individual and mean (SD) values for personal characteristics

	Lesion		Age (years)		TSI (years)	Weight (kg)	Height (cm)	Experience in hand cycling	Trained minutes weekly	Wheelchair daily use	
	Left	Right									ASIA
C7–C8											
1	C7C8		A	32	M	13	78	203	Yes	0	Hand rim
2	C6C7		B	22	M	2	86	195	Yes	30	Hand rim
3	C7C7		B	32	M	6	77	176	Yes	90	Hand rim
4	C7C7		B	54	M	28	81	174	Yes	120	Hand rim
5	C8C8		B	31	M	6	83	187	Yes	60	Hand rim
6	C7C7		B	64	M	3	88	165	Yes	0	Electric
7	C7C7		B	47	M	1.5	63	180	Yes	120	Hand rim
8	C6C7		B	29	M	7	69	177	Yes	30	Hand rim
9	C7T1		A	52	M	16	117	184	Yes	0	Hand rim
10	T1C8		B	45	M	2	64	180	No	0	Hand rim
Mean				40.8		8.5	80.6	182		45	
SD				13.5		8.4	15.5	11		50	
C5–C6											
11	C5C5		A	44	M	7.5	113	178	Yes	120	Electric
12	C6C6		B	37	M	15	85	186	Yes	120	Hand rim
13	C6C6		A	41	M	3	117	179	Yes	0	Electric
14	C6C6		B	58	F	42	81	173	No	0	Electric
15	C5C5		A	33	M	1.5	51	170	Yes	120	Both
16	C5C6		B	33	M	2.5	65	165	Yes	120	Both
17	C6C6		B	41	M	15	83	198	No	0	Electric
18	C5C6		B	46	F	7	80	172	No	90	Both
19	C5C6		A	32	M	3.5	77	188	Yes	0	Hand rim
20	C5C6		A	21	M	6	60	180	Yes	0	Both
Mean				38.6		10.3	81.2	179		57	
SD				9.9		12.1	21.0	10		60	
Mean (total)				39.7		9.4	80.9	181		51	
SD				11.6		10.2	17.9	10		54	

values for metabolic and HR parameters were measured during 5 min of sitting rest. Subsequently, the subjects familiarised with hand cycling on the treadmill during 2 min. In these minutes, the velocity of the treadmill and cadence of the hand cycle were adjusted to the ability of the subject within the range of 4–7 km/h and a cadence of approximately 60 r.p.m. After a 3 min rest following the familiarisation period, the subjects performed the discontinuous graded exercise test. Exercise bouts of 2 min were followed by 30 s of rest. In each exercise step, PO was increased with increments of 2.00–5.25 W, depending on the estimated individual capacity. This process continued until exhaustion or until the subject indicated that he/she wanted to stop. Average HR and $\dot{V}O_2$ -values over the last 60 s of each exercise bout were used for analysis. If the last uncompleted block exceeded more than 60 s, the HR and $\dot{V}O_2$ -value were included as well. The highest $\dot{V}O_2$ -value attained over 60 s during the test was defined as the $\dot{V}O_{2\text{peak}}$. Respiratory exchange ratio (RER) was calculated as the ratio between $\dot{V}CO_2$ and $\dot{V}O_2$. Rating of perceived exertion (RPE)²⁶ on the 10-point Borg scale was assessed

immediately after the end of the graded exercise hand cycle test. PO was increased – through a pulley system that was positioned behind the treadmill and connected to the rear wheel axle of the hand cycle by a rope²² – by adding extra weight (F_{add} in N). External PO was calculated from rolling resistance (F_{roll}), added load (F_{add}) and treadmill belt velocity (v) according to:

$$PO(W) = [F_{\text{roll}} + F_{\text{add}}]v \quad (1)$$

F_{roll} was determined in a separate drag test with the subject sitting passively in the hand cycle.²⁷

Hand cycle

Subjects were tested using their own rigid frame wheelchair and attach-unit hand cycle (Figure 1). If the subject did not own one, the rehabilitation centre provided a hand cycle. All hand cycles were equipped with a synchronous crank system and a bullhorn steer (Double Performance, Gouda, The Netherlands). The crank axis of the steering was positioned as low as possible.

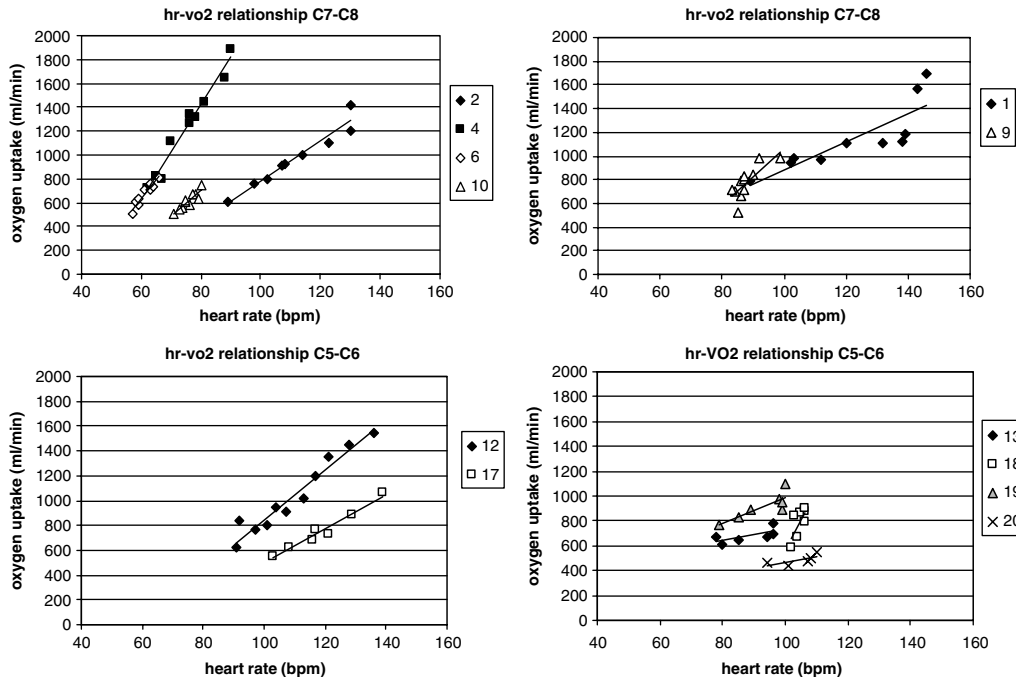


Figure 2 Typical examples of individual HR– $\dot{V}O_2$ regression lines of persons with a C7 or C8 lesion (a and b) and persons with a C5 or C6 lesion (c and d)

Statistics

For each participant, a linear regression analysis was performed and Pearson’s correlation coefficient (r) was calculated, using the paired data of $\dot{V}O_2$ and HR values of each exercise block. The actual error of the predicted $\dot{V}O_2$ from the regression equation is commonly^{10,14} reflected by the SEE, expressed in the units of measurement. To determine the accuracy of the $\dot{V}O_2$ prediction in the individual regression equations, the SEE was calculated according to:

$$SEE = s_{(\dot{V}O_2)}(1 - r^2)^{1/2} \quad (2)$$

where $s_{(\dot{V}O_2)}$ is the SD of the individual data points and r is the individual HR– $\dot{V}O_2$ Pearson’s correlation coefficient.

Because absolute values of $SEE(\dot{V}O_2)$ do depend on the individual range of $\dot{V}O_2$ (ie range between $\dot{V}O_{2\text{rest}}$ and $\dot{V}O_{2\text{peak}}$: $\dot{V}O_{2R} = \dot{V}O_{2\text{peak}} - \dot{V}O_{2\text{rest}}$), SEE is also expressed as a percentage of the individual $\dot{V}O_{2R}$. The SEE of $\dot{V}O_{2R}$, given a certain HR, can be interpreted the same way as the SD and the 95% confidence interval of the predicted value can be calculated. For example, a recommended range of training intensity of 60–85% HRR (is comparable to 60–85% $\dot{V}O_{2R}$ ²⁸) would allow an HR corresponding with 72% HRR (or $\dot{V}O_{2R}$) and $SEE \leq 6\%$ HRR (or $\dot{V}O_{2R}$) to actually train within this range. Statistical analyses were performed with SPSS 12.01 for Windows.

Results

In Table 2, the physiological characteristics are presented for all subjects divided over the C5–C6 and the

C7–C8 lesion group. All subjects attained the $\dot{V}O_{2\text{peak}}$ during the last exercise bout. It was found that 17 out of 20 subjects reached an RER above 1.00. Subjects 1 and 14 reached an RER of 0.97 and subject 6 an RER of 0.93. Eleven subjects scored an RPE of 6 or lower on the 10-point Borg scale. Two subjects (15 and 16) had a very low physical capacity and were able to complete only three exercise intervals of the peak capacity test. Because of the low number of data points, these subjects were excluded from the analysis. Table 3 shows Pearson’s r and SEE of the paired HR and $\dot{V}O_2$ for the remaining participants ($n=18$). Individual data points and regression lines of representative subjects of the C5–C6 group and the C7–C8 group are shown in Figure 2. Pearson’s r ranged from 0.68 to 0.97 (mean 0.81 ± 0.12) for the C5–C6 group and from 0.79 to 0.97 (mean 0.91 ± 0.07) for the C7–C8 group. The results of the $SEE(\dot{V}O_2)$ showed mean values of 57 ± 25 ml/min in the C5–C6 group and 67 ± 39 ml/min in the C7–C8 group. The $SEE(\% \dot{V}O_{2R})$ showed mean values of $10.6 \pm 5.6\%$ in the C5–C6 group and $7.0 \pm 3.2\%$ in the C7–C8 group, respectively. The mean r for the whole group was 0.87 ± 0.10 and the $SEE(\% \dot{V}O_{2R})$ was $8.6 \pm 4.6\%$.

In Table 3, it is shown that two subjects of the C5–C6 group and six subjects of the C7–C8 group attained a $SEE \leq 6.0\% \dot{V}O_{2R}$. All these subjects showed Pearson’s r of 0.90 or higher. In Table 4 mean values of PO_{peak} , HR_{peak} , HRR, $\dot{V}O_{2\text{peak}}$ and $\dot{V}O_{2R}$ of subjects with $SEE \leq 6.0\%$ ($n=8$) and $SEE > 6.0\% \dot{V}O_{2R}$ ($n=10$) are shown. These two groups showed no significant differences.

Table 2 Individual and mean (SD) values of the physiological characteristics of the graded maximal exercise hand cycle test

	<i>HR rest</i> (<i>b.p.m.</i>)	<i>HR peak</i> (<i>b.p.m.</i>)	<i>VO₂ rest</i> (<i>ml/min</i>)	<i>VO₂ peak</i> (<i>ml/min</i>)	<i>PO peak</i> (<i>W</i>)	<i>RER</i>	<i>Initial PO</i> (<i>W</i>)	<i>ΔPO block</i> (<i>W</i>)	<i>Duration test</i> (<i>min</i>)	<i>Borg</i>
<i>C7–C8</i>										
1	67	146	273	1690	57.6	0.97	4.9	5.2	30	7
2	54	130	327	1421	51.8	1.13	6.8	4.5	26	9
3	52	123	372	1464	66.8	1.12	8.3	4.5	32	9
4	47	90	380	1885	74.2	1.12	9.5	5.2	17	9
5	49	136	321	1265	61.6	1.02	6.5	5.2	25.5	8
6	50	66	328	813	23.7	0.93	2.7	2.0	24.5	5
7	66	127	223	1241	28.0	1.02	3.5	3.0	19	4
8	59	101	250	1097	43.0	1.06	5.6	5.2	14	6
9	64	92	290	978	29.0	1.12	6.0	2.0	29	6
10	49	80	200	743	30.0	1.10	3.5	2.0	33	5
Mean	55.7	111	296	1258	46.6	1.06	6.0	3.8	25	6.8
SD	7.7	28	60	370	18.3	0.07	2.5	1.5	6.5	1.9
<i>C5–C6</i>										
11	56	118	386	778	16	1.02	6.0	2.0	11.5	6
12	62	136	318	1550	74.3	1.13	9.5	5.2	31	9
13	60	96	316	782	32.0	1.08	7.7	3.8	11	6
14	66	116	401	844	23.7	0.97	3.1	2.5	17	8
15	54	99	248	962	12.0	1.38	4.0	2.0	8	5
16	68	128	287	729	14.0	1.19	4.0	2.0	8.5	7
17	87	129	432	882	28.6	1.06	3.0	2.5	15	6
18	77	106	270	900	20.6	1.01	3.0	2.0	16	7
19	52	100	250	1099	45.0	1.12	5.0	5.2	17.5	5
20	59	110	226	545	17.0	1.10	8.6	2.0	11.5	6
Mean	64.1	114	305	907	28.9	1.10	5.4	2.9	15	6.5
SD	10.9	14	60	269	18.5	0.12	2.4	1.3	7	1.3
<i>C5–C8</i>										
Mean	60	112	301	1083	37.7	1.08	5.7	3.4	20	6.7
SD	10.1	21	59	363	20.0	0.09	2.4	1.4	8	1.6

Discussion

The aim of this study was to examine the individual HR– $\dot{V}O_2$ relationships in subjects with TP to answer the question whether HR can be used to quantify exercise intensity in persons with TP. We found a satisfactory linear relationship in eight out of 18 subjects, indicating that HR is useful in some, but not all persons with TP.

Strength of the HR– $\dot{V}O_2$ relationship

According to the ACSM guidelines, a training intensity is prescribed as a range⁵; for example, training hard within 60–85% HRR or $\dot{V}O_2R$. With an estimated training intensity of 72% HRR or $\dot{V}O_2R$ and an SEE of 6% $\dot{V}O_2R$, it can be assumed with 95% confidence that the actual training intensity is between 60 and 84%. Therefore, in our opinion, an SEE of $\pm 6\%$ $\dot{V}O_2R$ is acceptable as it keeps training intensity within the required range. Eight out of 18 subjects had an SEE lower than the cutoff value of 6% and are assumed to have a satisfactory linear HR– $\dot{V}O_2$ relationship. All

these eight subjects also had a correlation coefficient of 0.90 or higher.

Well-trained athletes with a PP in studies of Goosey *et al*¹⁰ and Tolfrey *et al*¹⁴ showed much higher mean Pearson's *r*-values of 0.97 ± 0.02 and 0.99 ± 0.01 , respectively, as well as a lower SEE of 3.4 ± 1.4 and $2.6 \pm 1.0\%$ HR_{peak}, respectively, than subjects in the current study (see Table 3). Two other studies showed lower Pearson's *r*-values in subjects with PP, ranging from 0.85–0.99⁹ to 0.74–0.99.¹² Both studies concluded that a linear relationship exists, whereas the correlation coefficients, at least in some subjects, were rather low. The mean Pearson's *r*-values of our study are comparable with McLean *et al*²⁰ during arm cranking (mean *r* = 0.85) and higher than values presented by Coutts *et al*²¹ and Schmid *et al*¹³ (*r* = 0.65 and 0.69, respectively) during wheelchair propulsion. McLean *et al*²⁰ concluded that HR should not be used for prescribing exercise for individuals with TP because HR and $\dot{V}O_2$ are too variable to accurately reflect the work being carried out. Unfortunately, none of these authors presented their data with an SD or SEE.

Table 3 Individual and mean Pearson correlation coefficient and *SEE* of HR- $\dot{V}O_2$ data of the graded exercise test

	Lesion	HR- $\dot{V}O_2$ Pearson's r	P-value	Data points (n)	SEE ($\dot{V}O_2$) (ml/min)	SEE (% $\dot{V}O_2R$) (%)
C7-C8						
1	C7C8	0.85**	0.002	11	143	10.1
2	C6C7	0.97**	0.000	9	60	5.5
3	C7C7	0.86**	0.000	13	118	10.8
4	C7C7	0.97**	0.001	6	59	3.9
5	C8C8	0.97**	0.001	10	52	5.5
6	C7C7	0.96**	0.000	9	27	5.6
7	C7C7	0.97**	0.000	7	26	2.6
8	C6C7	0.82 ^{NS}	0.090	5	78	9.2
9	C7T1	0.79**	0.004	11	82	11.9
10	T1C8	0.92**	0.000	10	27	5.2
	Mean	0.91		9.1	67	7.0
	SD	0.07		2.5	39	3.2
C5-C6						
	Lesion					
11	C5C5	0.78 ^{NS}	0.117	5	88	22.4
12	C6C6	0.97**	0.000	11	74	6.0
13	C6C6	0.68 ^{NS}	0.138	5	41	8.8
14	C6C6	0.86*	0.026	6	58	13.2
17	C5C5	0.98**	0.000	7	34	5.4
18	C5C6	0.72 ^{NS}	0.066	7	82	13.0
19	C6C6	0.83*	0.022	7	59	7.0
20	C5C6	0.72 ^{NS}	0.172	5	29	9.0
	Mean	0.81		6.6	57	10.6
	SD	0.12		2.0	25	5.6
C5-C8						
	Mean	0.87		8.0	62	8.6
	SD	0.10		2.5	33	4.6

** $P < 0.01$ and * $P < 0.05$. NS = not significant

Table 4 Mean values of PO_{peak} , HR_{peak} , HRR, $\dot{V}O_{2peak}$ and $\dot{V}O_2R$ for subjects with $SEE \leq 6\%$ and $SEE > 6\%$

	$SEE \leq 6.0\%$ (n = 8)	$SEE > 6.0\%$ (n = 10)	P-value
PO_{peak}	47 ± 21 W	29 ± 12 W	0.230
HR_{peak}	112 ± 28 b.p.m.	112 ± 17 b.p.m.	0.934
HRR	55 ± 24 b.p.m.	51 ± 19 b.p.m.	0.729
$\dot{V}O_{2peak}$	1223 ± 399 ml/min	1018 ± 341 ml/min	0.255
$\dot{V}O_2R$	918 ± 373 ml/min	714 ± 346 ml/min	0.248

The above-mentioned studies indicate that a linear relationship exists in persons with a PP below Th4,^{9,10,12,14} but not in (all) persons with TP.^{13,20,21} In the current study, the HR- $\dot{V}O_2$ relationship was found to be linear in only eight out of 18 subjects. The unstable relationship in the other 10 subjects may be explained by the disturbed sympathetic innervation or other factors related to the low physical capacity and muscle mass involved.

The disturbed sympathetic system

Persons with TP have a low HR_{peak} and consequently often also a small HRR ($HR_{peak} - HR_{rest}$). Our results

show that a small HRR or low HR_{peak} , for example, in subjects 4, 6 and 10 (Figure 2a), does not necessarily result in a lower correlation coefficient or a higher SEE, as is shown in Table 4. This is not in agreement with Mc Lean *et al*,²⁰ who explained the higher HR- $\dot{V}O_2$ correlation in the supine position compared to the sitting position, by the significant higher range over which the HR can accelerate.

The severity of cardiovascular dysfunction after SCI correlates well with the severity of injury to the spinal motor and sensory pathways scored with the ASIA.²⁹ Nevertheless, in subjects with ASIA B and possibly even in ASIA A, there is still a chance of survival of some autonomic fibres that extend below injury level. It is

unclear from our results what the influence of the disturbed sympathetic system on HR or blood flow and O₂ transport to the muscles might have been in our subjects. From the study of Hjeltnes *et al.*,¹⁷ however, it appeared that the observed arterial PO₂ was low, but not the limiting factor during increased work loads in individuals with motor complete TP.

AD could also be responsible for a disturbed HR–VO₂ relationship owing to a sudden rise or fall in HR-values. However, subjects were screened before and throughout the test for symptoms of AD and no symptoms occurred. AD should be prevented because in some cases extremely high BP-values can even lead to death from cardiac dysfunction or a stroke.¹⁸

Physical capacity

Two subjects (15 and 16) had to be excluded from further analysis because they were not able to complete more than three blocks, despite very small increments per bout (2 W). A very low physical capacity is often seen in these subjects, especially in (untrained) persons with a C5–C6 lesion. Consequently, the influence of a measurement error (an outlier) or normal fluctuations in VO₂ will be relatively large, when only few data points are spread out over a small VO₂R. This may be a possible explanation for the lower correlation in some subject (13 and 20, see also Figure 2d). Subjects 12 and 17 (Figure 2c), both with a relatively large VO₂R, are the only subjects from the C5–C6 group with an acceptable Pearson's *r*.

However, our results show that a large VO₂R (eg subject 1 in Figure 2b) does not always result in a satisfactory linear relationship as is shown in our results: No significant differences in PO_{peak}, VO_{2peak} and VO₂R were found between the eight subjects with satisfying Pearson's *r* and SEE and the other 10 subjects, as is shown in Table 4. On the other hand, it seems that an extremely low physical capacity and VO₂R always coincides with an unstable HR–VO₂ relationship.

Limitations of the study

It was beyond the scope of the current study to clarify the influence of the disturbed sympathetic system on the individual HR–VO₂ relationship in persons with TP. However, it would be interesting in future to investigate the influence of the sympathetic system on the HR–VO₂ relationship during exercise as well: by measuring BP, catecholamine concentration¹³ and blood gas, as was performed by Hjeltnes *et al.*¹⁷ or by analysing the beat-to-beat HR variability³⁰ or BP variability.³¹

Moreover, it should be remarked that in this study we have not looked into the reproducibility of the found regression equations. It may be possible that the day-to-day variability has an influence on the individual regression equations. Even in able-bodied people intraindividual variability can be substantial between days.³²

Practical implications

Results of this study showed that HR is useful in some, but not all, individuals with TP to monitor training intensity. The Borg scale may be a possible alternative, indicating the overall perceived exertion. However, the rather low RPE values at the end of the test and the reported local (arm) muscle soreness as reason for stopping indicate that using the Borg scale to monitor training intensity has severe limitations for persons with TP. Another option to monitor training intensity is continuously monitoring of PO and subsequently training at %PO_{peak}. For hand cycling commercially available power measuring crank systems used in cycling, may be suitable. However, to our knowledge, the validity and reliability has not been tested in hand cycling at low PO levels seen in persons with TP.

Conclusion

From our data, it appears that the HR–VO₂ relationship was found to be linear in eight out of 20 individuals with an acceptable SEE(%VO₂R) ≤ 6.0% and a *r* > 0.90. Therefore, HR can be used in some, but not all, individuals with TP to monitor training intensity. No single reason such as a low HRR as a consequence of the disturbed autonomic nervous system, AD or the limited physical capacity could be indicated to explain the HR–VO₂ relationship. It is therefore likely that a combination of these factors is responsible for the lack of a linear HR–VO₂ relationship. Our results, however, did not allow elucidating the underlying mechanisms why some subjects have, and others do not have, a useful HR–VO₂ relationship. It is concluded that the use of HR as an indicator of training intensity should be reconsidered in persons with TP: An individual analysis of the HR–VO₂ relationship is necessary to determine whether HR can be used to prescribe exercise intensity. Further research should focus on the test–retest reliability and alternative indicators of training intensity such as percentage peak PO should be explored.

Acknowledgements

This study was supported by ZON-MW (Grant number: 014-32-012), The Netherlands Organisation for Health, Research and Development, The Hague.

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