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Comparison of Physiological Responses to Maximal Arm Exercise Among Able-bodied, Paraplegics and Quadriplegics

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Summary

A comparison of pulmonary, cardiovascular and metabolic responses was made in 32 subjects consisting of 11 able-bodied, 8 paraplegics (T4–L3 lesions) and 13 quadriplegics (C5–C8 lesions) during maximal arm cranking exercise. A progressive continuous arm cranking test, modified for each group, was employed to elicit maximal responses with pulmonary and metabolic determinations made with open circuit spirometry and selected cardiovascular measurements made by impedance cardiography. Additionally, non-exercise static and dynamic lung function assessments were made. Quadriplegics had significantly lower ($p < 0{\cdot}05$) tidal volumes, vital capacities, forced expiratory volumes at 1 seconds, and maximal breathing caapacities than the other two groups. The mean peak $\mathring{V}O_2$ during maximal arm cranking was 28·2, 25·3 and 12·0 ml/kg.min for the able-bodied (AB), paraplegics (PP) and quadriplegics (QP), respectively. Furthermore, reduced cardiovascular function was observed in the QP as evident in the low peak HR (109 b/min), peak SV (52 ml/b) and peak $\mathring{Q}$ (5·7 l/min). Values for the QP were 64% and 64% peak HR, 89% and 50% peak SV and 54% and 33% peak $\mathring{Q}$ of values observed for the PP and AB groups, respectively. The peak SV and $\mathring{Q}$ values were significantly lower ($P < 0{\cdot}05$) for the PP group when compared with the AB group. Although not statistically significant the estimated a-v O_2 difference was higher for both spinal cord injured groups (14·0 and 14·6 ml O_2/100 ml, PP and QP respectively). The impaired work capacity and reduced oxygen transport and utilisation of the QP group can be attributed to impaired sympathetic cardiac stimulation and a smaller available active muscle mass.

Key words: *Paraplegics; Quadriplegics; Arm cranking; $\mathring{V}O_2$ peak; Exercise; Stroke volume; Cardiac output.*

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Introduction

The metabolic and circulatory responses to various modes of exercise have been studied extensively in able-bodied individuals. Investigators have examined the adaptability and limitations of both the central and peripheral circulatory systems to exercise modalities using different muscle groups (Astrand and Rodahl, 1977; Astrand and Saltin, 1961; Bevegard *et al.*, 1966; Magel *et al.*, 1978; Reybrouck *et al.*, 1975; Stenberg, 1966 and Stenberg *et al.*, 1967). Additionally, arm cranking has been used to assess physiological function in disabled individuals such as paraplegics and quadriplegics (Bevegard *et al.*, 1966; Gass and Camp, 1984; Hjeltnes, 1977; Pollock *et al.*, 1974; Wicks *et al.*, 1977–78; Zwiren and Bar-Or, 1975). Available data, however, has been limited to acute and chronic effects of exercise on metabolic and ventilatory parameters. Few data are available on circulatory function, i.e. cardiac output, stroke volume and arteriovenous oxygen difference in spinal cord injured (SCI) individuals (Hjeltnes, 1977; Sawka *et al.*, 1980). These studies reported similar circulatory function values for low level paraplegics when compared with able-bodied individuals while performing arm cranking exercise. Research evaluating the responses of the quadriplegic, primarily, has been restricted to measures of metabolic and ventilatory function during arm exercise. Virtually no information on functions such as cardiac output, stroke volume, and arteriovenous oxygen differences is available.

The purpose of this study was to characterise the metabolic and cardiovascular functions of quadriplegics and paraplegics during arm exercise and to compare these results with reference data of able-bodied individuals.

Subjects and methods

Thirty-two male and female subjects (11 able-bodied and 21 disabled) were recruited to participate in this study with written informed consent obtained from each individual. The subjects were divided into three groups according to their level of spinal cord injury: Group 1 Able-bodied (AB, N = 11) Group 2 Paraplegic with spinal cord lesion level T4–L3 (PP, N = 8), Group 3 Quadriplegic with spinal cord lesion level C5–C8 (QP, N = 13). Some of the subjects considered themselves to be wheelchair athletes and participated in activities such as basketball, archery and track. Each subject was required to make three visits to the laboratory. On the first visit each subject was given a formal orientation to the test procedures, consisting of familiarisation with the arm cranking instrument and accessories, i.e. mouthpiece, noseclip, the pulmonary function apparatus, and a neurological examination to determine the spinal lesion level. On the second visit the subject completed a 24-hour health and activity recall questionnaire and underwent both the pulmonary function tests and the maximal arm cranking test. The third visit was a replication of the pulmonary function and maximal arm cranking tests performed on the second visit (retest).

Descriptive measurements

Body weight and height were measured on each subject. Body weight was obtained on the disabled subjects by having the subject sit in a modified wheelchair on the scale the appropriate correction factor for the wheelchair was then subtracted from the total weight. All subjects were weighed while fully clothed but without shoes and/or orthopaedic braces. Weight was recorded to the nearest 100 grams. Height was measured, for the disabled subjects, while in an extended supine position on an examination table using a metal tape measure. For the able-bodied, height was taken while standing erect with their back against a stadiometer. Height was read and recorded to the nearest millimetre.

A 10-litre Collins spirometer, with motorised kymograph, was used to measure tidal volume (TV), forced vital capacity (FVC), forced expiratory volume in one second ($FEV_{1 \cdot 0}$), from which FEV/FVC was calculated, and maximum breathing capacity (MBC). Spirometry measurements were performed in the sitting position for all subjects.

Cardiovascular measurements

Cardiac stroke volume was assessed using a non-invasive system, the IFM/-Minnesota Impedance Cardiograph (Kubicek *et al.*, 1966; Miller and Horvath, 1978). Procedurally, four strip electrodes (Electronic for Medicine, Greenwich, CT) were attached to the subject. A constant high frequency, sinusoidal, alternating current (I) was passed through the thorax between the two outer most electrodes (1 and 4). The product of this current (I), multiplied by the thoracic impedance (Z) measured between the two inner most electrodes (2 and 3), generated a voltage (E) of $E = I \times Z$. This voltage was then measured by a high input linear impedance amplifier. The outputs were as follows: (1) Z = impedance between electrodes 2 and 3 (ohms); (2) SV = stroke volume (ml); (3) L = the distance between electrodes 2 and 3 (cm); (4) p = resistivity of blood as a function of hematocrit ($53.2^{0 \cdot 022_{HCT}}$); (5) dZ/dT = rate of change of the impedance tracing (ohms/sec.); (6) T = ventricular ejection time (sec.). Hematocrit was determined for each subject. Stroke volume was calculated from the following formula:

$$SV\ (ml) = p \times (L/Z)^2 \times dZ/dT \times T$$

Heart rate (b/min) was measured electrocardiographically. The electrocardiogram was recorded during the last 15 seconds of each workload. Additionally, arteriovenous oxygen difference (a-v O_2) was calculated by dividing peak oxygen consumption by cardiac output ($\mathring{V}O_2/\mathring{Q}$).

Metabolic measurements

Oxygen consumption ($\dot{V}O_{2\ stpd}$, l/min), carbon dioxide production ($\mathring{V}CO_2$, l/min), pulmonary ventilation ($V_{E\ btps}$, l/min), O_2 pulse and respiratory exchange ratio (R) were obtained by open circuit spirometry while subjects breathed through a two-way respiratory valve (Collins). One minute aliquots of expired gas were collected in metallised polyethylene bags (Johnson *et al.*, 1967) and analysed for oxygen and carbon dioxide. Gas analysers were calibrated with references gases of known concentration, previously determined by the micro-Scholander technique. Minute volumes of expired gases were measured by a dry gasometer (Parkinson-Cowan CD-4) that was previously calibrated against a 120-litre Tissot gasometer.

Table I Physical characteristics and pulmonary function of able-bodied, paraplegic and quadriplegic subjects

Group	N	Age yrs	Lesion level	HT cm	WT kg	TV l	FVC l	$FEV_{1.0}$ l	FEV/FVC %	MBC l/min
Able-bodied	11	26·2	—	176·3	71·2	0·94[a]	5·5[a]	4·5[a]	81	152·1[a]
		±1·2		±3·6	±4.6	±0·1	±0·4	±0·3	±2	±12·7
Paraplegic	8	25·2	T4–L3	170·3	60·2	0·86[a]	4·6[a]	3·8[a]	84	133·8[a]
		±2·9		±3·7	±2·8	±0·2	±0·4	±0·3	±3	±11·1
Quadriplegic	13	29·6	C5–C8	176·0	62·2	0·64[b]	3·1[b]	2·7[b]	85	94·3[b]
		±2·5		±2·3	3·4	±0·1	±0·2	±0·1	±3	6·3

Values are means ± Standard deviations; different superscripts indicate significant differences ($p < 0·05$).

Table II Metabolic parameters of able-bodied, paraplegic and quadriplegic subjects to maximal effort arm cranking exercise

Group	N	Workload Kpm/min	VO_2 l/min	VO_2 ml/Kg/min	VCO_2 l/min	R	O_2 Pulse ml/b
Able-bodied	11	584	2·1[a]	28·2[a]	2·4[a]	1·15[a]	12·7[a]
		±67	±0·9	±6·8	±1·0	±0·07	±5·4
Paraplegic	8	522	1·5[b]	25·3[a]	1·7[b]	1·14[a]	9·7[ab]
		±80	±0·6	±7·4	±0·8	±0·22	±4·2
Quadriplegic	13	141	0·8[c]	12·0[b]	0·7[c]	0·92[b]	7·5[bc]
		±18	±0·2	±3·3	±0·3	±0·16	±2·0

Values are means ± standard deviations; different superscripts indicate significant differences ($p < 0·05$).

Test protocol

Arm cranking was performed on a modified Monarch bicycle ergometer. The arm crank unit was inserted into the seat support of the Monarch and secured by two bolts. A chain and sprocket coupled the arm crank to the flywheel of the Monarch maintaining standard gearing of the bicycle such that one arm crank revolution resulted in the flywheel travelling a distance of 6 metres. A speedometer was observed by the subject to maintain the required velocity. In addition, an electronic metronome was used to aid the subject in cranking at the prescribed speed (50 rpm). An adjustable chair was mounted in a hydraulic lift so that the subject could be positioned with the shoulders level and in-line with the arm crank. Each subject performed a progressive, continuous arm-cranking test including a 2 minute warm-up bout and 2 minute progressive exercise bouts until volitional exhaustion. The starting workload for the quadriplegics (QP) was set at 75 kpm/min with increments of 75 kpm/min every 2 minutes. The workload for the paraplegics (PP) and able-bodied (AB) subjects was set at 150 kpm/min with increases of 150 kpm/min every 2 minutes. Testing was terminated at the subject's volitional point of exhaustion.

Statistical analyses included descriptive statistics and analysis of variance to test the significance of differences between groups. The 0·05 level of significance was used to determine significant differences.

Results

The physical characteristics and pulmonary function data for the three groups are presented in Table I. Analysis of the pulmonary data indicated that the quadriplegics had significantly lower values than did the able-bodied and paraplegic subjects for all variables except FEV/FVC.

Values for metabolic parameters recorded during the minute of exercise when peak oxygen consumption was achieved are shown in Table II. The analysis between groups showed significant differences between all three groups for VO_2 and VCO_2 (l/min). Significantly lower values were observed for the QP group compared to the PP and AB groups for VO_2 when expressed relative to body weight (ml/kg/min). The difference between the three groups appears to be related to spinal lesion level (Fig.). The data plotted in this figure demonstrate that lower values were obtained on the QP subjects compared to the PP and AB subjects. Likewise, the similarities in VO_2 ml/kg/min for the PP and AB groups are illustrated. The O_2 pulse (ml/b) values for the QP group were similar to those of the PP group but significantly lower than those obtained on the AB group. The QP subjects also had significantly lower values for respiratory exchange ratio (R) compared to the other two groups.

Pulmonary and ventilatory responses to the arm cranking exercise are displayed in Table III. The QP group again demonstrated significantly lower values than the other two groups for pulmonary ventilation ($V_{E\ btps}$ l/min) and tidal volume (l). There was no difference between groups for respiratory rate and ventilatory equivalent (l/100 ml O_2).

The peak cardiovascular responses to the arm cranking exercise are shown in Table IV. The QP group had significantly lower values for all parameters, except a-v O_2 difference, when compared to the PP and AB groups. In addition, the PP subjects had significantly lower values for stroke volume (ml/b), cardiac output

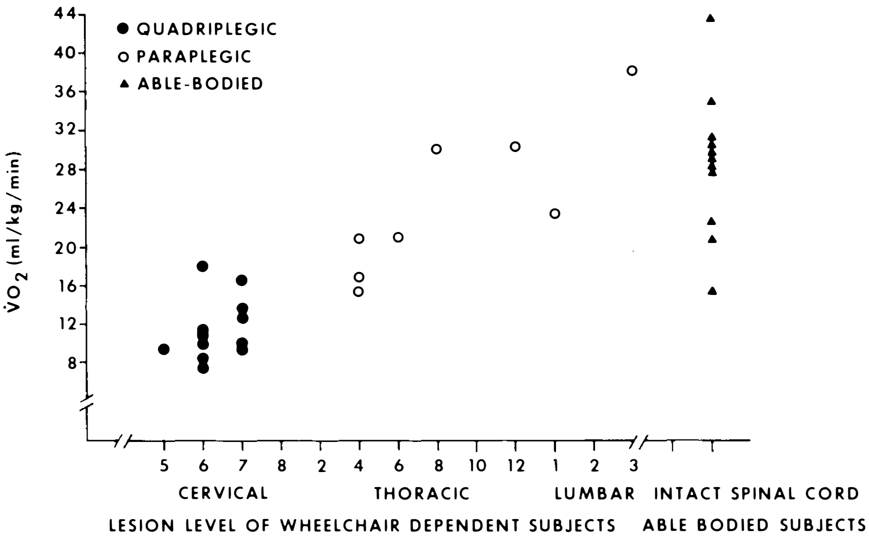

Figure Relationship between spinal cord injury and peak oxygen consumption during arm cranking exercise.

Table III Pulmonary and ventilatory responses of able-bodied, paraplegic and quadriplegic subjects to maximal effort arm cranking exercise

Group	N	V_E(BTPS) (l/min)	Respiratory rate (br/min)	VE/VO$_2$ l/100 ml O$_2$	Tidal volume (l)
Able-bodied	11	84·3[a]	40[a]	3·5[a]	1·9[a]
		±36·9	±9	±0·6	±0·7
Paraplegic	8	68·7[a]	42[a]	4·0[a]	1·4[a]
		±32·7	±7	±0·7	±0·5
Quadriplegic	13	26·6[b]	33[a]	3·3[a]	0·8[b]
		±8·3	±7	±0·7	±0·2

Values are means ± standard deviations; different superscripts indicate significant differences ($p < 0·05$).

Table IV Cardiovascular responses of able-bodied, paraplegic, and quadriplegic subjects to maximal effort and cranking exercise

Group	N	HR b/min	SV ml/b	Q l/min	Q index l/m^2	A-V O$_2$ diff
Able-bodied	11	168[a]	104·3[a]	17·2[a]	9·2[a]	12·8[a]
		±14	±23·8	±3·2	±2·0	±4·5
Paraplegic	8	160[a]	58·4[b]	10·5[b]	5·9[b]	14·6[a]
		±32	±35·4	±5·6	±3·0	±2·8
Quadriplegic	13	109[b]	52·0[c]	5·7[c]	3·23[c]	14·0[a]
		±17	±8·6	±1·3	±0·8	±5·0

Values are means ± standard deviations; different superscripts indicate significant differences ($p < 0·05$).

(l/min), and cardiac index (l/m^2 BSA) when compared with the AB subjects. Although statistically insignificant, the QP and PP groups demonstrated slightly higher values for a-v O$_2$ difference when compared to the AB group.

Discussion

The results of the present study reflect the physiological characteristics of men and women from three different neurologial classificiations: able-bodied, paraplegics and quadriplegics. The pulmonary function results for the able-bodied subjects are similar to those reported by Zwiren and Bar-Or (1975). The values for the paraplegics, in the present study, were in the range of values reported by Hjeltnes (11977) and Zwiren and Bar-Or for both sedentary and active wheelchair dependent individuals. In contrast, the paraplegic values for FVC, $FEV_{1·0}$ and FEV/FVC were below those values of Gass and Camp (1984) for highly trained wheelchair athletes. These differences in pulmonary function, in the present study, and those reported by other investigators (Gass and Camp, 1979; Glaser *et al.*, 1980; Sawka *et al.*, 1980) may be attributed to grouping all of the paraplegics, i.e. men and women, active and sedentary, into one group and/or not separating the PP group into high and low lesion levels.

Reseach in the area of central circulatory responses to exercise with differing amounts of muscle mass, e.g. arms vs. legs, has suggested that an increase in muscle mass results in a larger oxygen consumption, higher ventilation, larger

O_2 pulse, larger cardiac output and an increased maximal heart rate (Astrand and Rodahl, 1977; Astrand *et al.*, 1964; Astrand and Saltin, 1961; Bevegard *et al.*, 1966; Magel *et al.*, 1978; Reybrouck *et al.*, 1975; Rowell, 1974 and Stenberg *et al.*, 1967). It would, therefore, be reasonable to expect higher physical work capacities in subjects with a larger functional muscle mass. The work of Coutts *et al.* (1983) demonstrated significant differences in $\mathring{V}O_2$ (l/min) between quadripegics, high level paraplegics and low level paraplegics.

Additionally, significantly lower heart rates were observed for the quadriplegics compared with both the high and low level paraplegics. Similarly, Gass and Camp (1979) reported significantly lower values for $\mathring{V}O_2$ (l/min) between quadriplegics and high and low level paraplegics as well as a lower maximal heart rate for the quadriplegic subjects compared to all of the other paraplegic subjects. In the present study, all three groups demonstrated significantly different values for peak oxygen consumption (l/min), with the AB subjects achieving the highest values and the PP and QP subjects obtaining lower values.

The peak $\dot{V}O_2$ (l/min) values for the paraplegics were lower than those reported by Gass and Camp (1979) and Glaser *et al.* (1980), within the range of values reported by Hjeltnes (1977) and Zwiren and Bar-Or (1975) but higher than those reported by Wicks *et al.* (1977–78). The peak $\mathring{V}O_2$ values achieved by the QP, in the present study, are lower than those reported by Coutts *et al.* (1983), Gass and Camp (1979) and Wicks *et al.* (1977–78).

The maximal heart rate recorded by Coutts *et al.*, Gass and Camp and Wicks *et al.*, indicated a significantly lower heart rate for the quadriplegics compared with the paraplegics during arm exercise. Similarly, significantly lower maximal heart rates were observed for the QP compared to the PP and AB subjects in the present study. This lower heart rate for the quadriplegic subjects may be attributed to a reduced sympathetic stimulation (neuronal and circulating catecholamines) as well as other possible factors (neurogenic, humoral, temperature, etc.) resulting from a lower metabolic rate and smaller active skeletal muscle mass. More research in this area is necessary before a conclusion can be drawn.

Central and peripheral circulatory function, as measured by stroke volume (ml/b), cardiac output (l/min), and a-v O_2 difference (ml/100 ml), have been reported previously for paraplegics (Hjeltnes, 1977) but not for quadriplegic individuals. The results for the able-bodied individuals in this study can be compared with the work of Astrand *et al.* (1964), Astrand and Saltin (1961), Bevegard *et al.* (1966) and Stenberg *et al.* (1967). The values for the able-bodied individuals are within the range of values reported by these other investigators for arm exercise, i.e. approximately 75% of maximal leg exercise values. However, the values for cardiac stroke volume and cardiac output for the paraplegics and quadriplegics were significantly lower than those of the able-bodied subjects. The cardiac output of the PP in the present study are within the range of values reported by Hjeltnes (1977), i.e. 5 to 15 l/min. Similarly, the stroke volume for the paraplegics, in this study, are in agreement with the values reported by Hjeltnes (1977; Table IV).

Furthermore, the QP demonstrated values for stroke volume and cardiac output that were lower than those obtained by the PP group. The lower stroke volumes recorded for both wheelchair dependent groups may be related to a decreased venous return to the heart as a consequence of a reduced active muscle pump in the lower limbs. In the case of the PP, the decreased cardiac input does not appear to be the result of a decreased heart rate since the heart rate for the PP group was similar (160 b/min) to the AB group (168 b/min). Although the exercise mode consisted of arm cranking, the able-bodied subjects were capable of movement in the lower torso as well as secondary muscular contractions in the lower limbs as the workload was increased. These secondary muscle contractions may aid the venous return to the heart and thus assist in maintaining the stroke volume and cardiac output. This would be expected during arm exercise when an active muscle pump from the lower extremities has been limited.

In contrast, the lower cardiac output of the QP subjects resulted from a combination of a lower stroke volume and a lower heart rate during exercise. Interestingly, the three groups showed no significant differences in their a-v O_2 difference. Unlike the results reported by Hjeltnes (1977) for paraplegics, the values reported in this study are similar to those reported for able-bodied individuals during arm exercise, i.e. approximately 70% of the theoretical maximal value. These values for the a-v O_2 differences are indicative of normal oxygen extraction in the periphery, suggesting that the regional blood flow to the working muscles was normal.

In conclusion, the present investigation found that in a mixed sample (males and females) of able-bodied and wheelchair dependent individuals significantly lower values for tidal volume (l), forced vital capacity (l), $FEV_{1 \cdot 0}$ and MBC (l/min) were observed for quadriplegic subjects compared with paraplegic and able-bodied subjects. Furthermore, significantly lower values for $\mathring{V}O_2$ (l/min), $\mathring{V}O_2$ (ml/kg/min), $\mathring{V}CO_2$ (l/min), O_2 pulse (ml/b), stroke volume (ml/b), cardiac output (l/min), and cardiac index (l/m^2 BSA) were obtained for both the PP and QP groups compared to the observed values for the AB group. These differences may be attributed to a reduction of active muscle mass and/or impaired sympathetic innervation resulting in a lack of cardiac acceleration during exercise, and may have been responsible for hypokinetic circulation, which diminishes circulatory pressure, resulting in a reduced venous return. Further research is needed for a better understanding of these complex mechanisms.

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