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BLOOD REDISTRIBUTION AND CIRCULATORY RESPONSES TO SUBMAXIMAL ARM EXERCISE IN PERSONS WITH SPINAL CORD INJURY

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ABSTRACT. The purpose of this study was to evaluate responses to submaximal arm exercise (20%, 40%, and 60% of peak power output) using four conditions to support the circulatory redistribution in persons with spinal cord injury (SCI). Five males with tetraplegia (TP) and four males with paraplegia (PR) exercised 1) sitting, 2) supine, and 3) sitting with the addition of a) an anti-gravity suit (anti-G), b) elastic stockings and abdominal binder, and c) functional electrical stimulation of the leg muscles. Compared to sitting, the following significant changes were observed: in the supine position, heart rate (HR) decreased (PR: 104 vs 118 b/min, TP: 76 vs 92 b/min) and stroke volume (SV) increased (PR: 132 vs 116 ml, TP: 96 vs 83 ml). The anti-G suit induced a decrease in heart rate (PR: 104 vs 118 b/min, TP: 87 vs 92 b/min) and a decrease in oxygen uptake (VO_2) in PR. Stockings only affected TP, i.e. a decrease in heart rate with 5 b/min and an increase in stroke volume with 13 ml/beat. Functional electrical stimulation produced an increase in VO_2 (PR: 1.00 vs 0.95 l/min, TP: 0.68 vs 0.53 l/min) and a rise in stroke volume in TP. Results indicate that the methods employed to support the circulatory redistribution have different working mechanisms and, in addition, that the effects are different for TP and PR probably because of differences in active muscle mass, sympathetic impairment and blood pressure values.

Key words: functional electrical stimulation, lower body negative pressure, paraplegia, supine exercise, support stockings, tetraplegia.

INTRODUCTION

During exercise in able-bodied subjects, a redistribution of blood takes place in order to elevate end-diastolic ventricular volume, stroke volume, and cardiac output. In this way, the exercising muscles are supplied with an elevated blood flow to compensate for the increased oxygen and substrate demands, and for the removal of metabolic by-products (1, 24). In individuals with spinal cord injury (SCI), however, these physiological adjustments to exercise are impaired. Several studies have shown that during voluntary arm exercise in SCI (5, 15, 19, 20) the circulatory adjustment is disturbed due to the absence of sympathetic vasoconstriction below the spinal cord lesion, as well as the lack of muscle pump activity in the lower limbs. Both of these factors may result in a disturbed redistribution of blood from the splanchnic and pelvic areas and from the legs. The degree of disturbance in blood redistribution varies depending on the level of the spinal cord lesion. As a consequence, the elevation in end-diastolic ventricular volume abates compared to able-bodied persons. In accordance with the Frank-Starling mechanism, stroke volume will not increase in SCI persons during arm exercise as is typically seen in a non-SCI control group (13).

Because a reduced stroke volume can be a limiting factor for a rise in cardiac output, oxygen transport and exercise capacity may be impaired in SCI. Several methods which increase the redistribution of blood in persons with SCI have been explored. Among these is the use of a supine position during arm exercise to minimize venous blood pooling and enhance end-diastolic ventricular volume. Some investigators (8, 9, 21) found cardiac output, VO_2, and power output to be higher, whereas others (18) did not observe any differences in physiological responses during exercise in supine versus sitting position in individuals with SCI. A second method is the application of lower-body positive pressure by means of an anti-gravity (anti-G) suit, which may decrease venous blood pooling in the legs and abdominal area. The anti-G suit has been shown to reduce heart rate at a given VO_2 during submaximal arm exercise in individuals with paraplegia (PR) (12) and to increase VO_2 and power output in individuals with tetraplegia (TP) (23). In rehabilitation centres, support stockings and abdominal binders have been used for a similar purpose. However, the effect of stockings and binders on the redistribution of blood in SCI persons has not been evaluated to our knowledge. Another method used to support the circulation is functional electrical stimulation (FES) of the paralysed lower limb muscles (4, 7, 11, 17, 22, 25). FES increases the amount of active muscle mass and may stimulate the legmuscle pump to drive more blood out of the lower part of the body, which may result in an increased end-diastolic ventricular volume. Davis et al. (4) reported an increase in stroke volume and cardiac output in persons with PR, and Phillips & Burkett (22) have reported an increase in **V**O_2 in TP and PR, both studies using static FES. Hooker et al. (17) demonstrated an increase in O_2 and heart rate during dynamic FES in persons with TP.

Although numerous effects of these four methods on cardiovascular responses during exercise in SCI persons have been reported, the use of different tests and different types of subjects makes it impossible to compare the studies and may account for the disparity in results. To elucidate the differences in effect these methods have on cardiovascular responses in individuals with SCI, one study has to be done that involves all conditions as well as individuals with different levels of SCI. The latter is of high importance since the level of the lesion determines to a great extent the disturbance in circulatory adjustment during exercise and consequently the effect a condition will have on circulatory responses.

The purpose of this study is to compare the cardiovascular responses of subjects with different lesion levels (TP and PR) during submaximal arm-cranking exercise in a sitting position to those obtained in the supine position, and sitting with the addition of the anti-G suit, support stocking and abdominal binder, and FES of the lower limb muscles.

MATERIAL AND METHODS

Subjects

Five males with TP and four males with PR participated in this study after giving their written informed consent. The study was approved by the Arizona State University Human Subject Institutional Review Board. All TP had complete spinal cord lesions (four individuals C5 and one C6), whereas the PR group had one incomplete lesion (T12) and three complete lesions (T7, T10, T12). Lesion level was verified by a physician using sensory and motor testing. All subjects were at least two years post-injury and underwent a medical examination including medical history and a screening questionnaire, cardiac and pulmonary auscultation, and neurological examination. None of the subjects had cardiopulmonary disease or used medications likely to affect the results of the study. All subjects were low to moderately trained as determined by interview and questionnaire.

Protocol

Subjects performed six arm-cranking exercise tests on separate days. During these tests, temperature and relative humidity were kept between 20°C to 23°C and 35% to 40%, respectively. Subjects refrained from using caffeine, nicotine, and alcohol at least two hours before each test.

In order to minimize the chance that bowel or bladder distension could produce autonomic dysreflexia during exercise, subjects performed a bowel program the night before or the morning of the day of the exercise test. Subjects on an intermittent catheterization program voided immediately before exercise testing. During the first visit following the medical examination, subjects were weighed in a sitting position. A screening FES-test was performed to assess subjects' response and tolerance to FES: After a short familiarization period, each subject performed a maximal arm ergometer test in the seated position using a continuous, multi-stage protocol to determine peak power output. Following this pretest, five submaximal exercise tests were performed in the following conditions: sitting, supine, and sitting with the addition of an anti-G suit, stockings and abdominal binder, and FES of the paralysed leg muscles.

The conditions were assigned in random order using a counterbalanced design. All tests were conducted at the same time of day for each subject with at least one day in between. The tests consisted of submaximal exercise at 20%, 40%, and 60% of power output peak as determined in the pretest, with each exercise bout lasting seven minutes followed by a five-minute rest period. Before the next exercise bout was started, the subject's heart rate had to be below rest-heart rate plus 10% to ensure full recovery. Steady-state exercise was verified by **V**O_2 and heart rate during the last two minutes of each stage (Fig. 1).

Materials

Exercise was performed using a Combi System 5 Cardiac Rehabilitation Cycle Ergometer (Combi Co. Ltd. Tokyo) adapted for upper-extremity use. A special frame allowed the same ergometer to be used for both the supine and sitting tests.

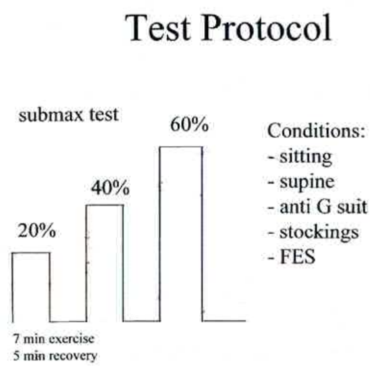

Fig. 1. Experimental protocol for the submaximal exercise test (submax test). The five conditions were assigned in counterbalanced order.

During each test, the pedal axis was aligned with the shoulder and the subject was positioned such that the elbow was still slightly flexed at maximal extension. All subjects were stabilized in their chairs using chest straps, and for the subjects with TP the hands were secured to the crank handles using specially-designed mitts.

The anti-G suit (Anti-G Garment Cutaway CSU-13B/P) consisted of five interconnected bladders (two calf, two thigh, and one abdominal bladder) with neither the hip nor the knee areas covered. The suit was inflated using a foot pump to a pressure of 55 mmHg. This value allows for the application of pressure to the venous system with negligible effect on the arterial vessels. To prevent any risk or discomfort for the subjects, the suit was deflated for five minutes between each exercise stage.

Support stockings and abdominal binders are commonly used in rehabilitation centres to support circulation in persons with SCI. In order to assess the effects that these have on exercise performance in SCI-individuals, these treatments were included in this study. The stockings (Anti-Embolism Stockings Bell-Horn, Freeman Health Care Products) were knitted to create the greatest amount of elastic pressure at the ankle, with decreasing pressure up the leg. Stockings were available in small, medium, large and extra large sizes. The size used depended on the calf and thigh circumferences of the subject. The abdominal binder (Multiple Use Elastic Binder, model 975, Freeman Health Care Products) was available in small, medium and large sizes, and was easy adaptable for all subjects. Pressure levels generated by the stockings and binder vary between 10 and 30 mmHg.

FES was applied to both lower limbs with two EMPI "Focus" Neuromuscular Stimulators (EMPI Inc. St. Paul, Minnesota) over the motor point of each muscle (quadriceps, hamstrings, gastrocnemius and tibialis anterior) via bifurcated leads and self-adhesive reusable electrodes (EMPI). Stimulation consisted of symmetric biphasic pulses of 300 Ms at 35 Hz delivered across a 1000 ohm load at 80 milliamperes (mA), over a duty cycle of 2.5 seconds "on" and 5 seconds "off" with a 2-second "rise" and "fall" time for each pulse, according to the protocol used by Phillips & Burkett (22). During the five-minute rest periods between the exercise stages, FES was turned off to minimize leg-muscle fatigue.

Measurements

During all tests, **V**O_2, carbon dioxide output (**V**CO_2), and ventilation were measured continuously by open-circuit spirometry and averaged over 20-second intervals using a Horizon Metabolic Cart 2900 (Sensormedics Corp.). The cart was calibrated before each test using known gas mixtures. The subjects breathed through a Hans Rudolph valve (Automatic Cardiac Output CO_2 rebreathing valve setup, Series 8200, Hans Rudolph Inc.).

The ECG was recorded during the last 20 seconds of each minute and heart rate was calculated as the mean of the last two minutes of the submaximal exercise bout.

Blood pressure was measured manually by the same examiner using a standard sphygmomanometer at rest and immediately after cessation of each stage of exercise. Mean arterial blood pressure (MAP) was calculated from systolic (SBP) and diastolic blood pressure (DBP), i.e. [DBP + (SBP − DBP)/3]. Total peripheral resistance was calculated by MAP/**Q**.

Subjects indicated their overall rating of perceived exertion using the Borg scale (2) immediately upon completion of each exercise stage.

Cardiac output (**Q**) was determined indirectly during the last minute of each submaximal stage using the CO_2-rebreathing method according to Collier (3). Mixed-venous CO_2 tension ($PvCO_2$) was determined from the CO_2 plateau (Sensormedics 2900 Metabolic Cart) with an additional "downstream" correction factor (14). Arterial CO_2 tension ($PaCO_2$) was calculated from the modified Bohr Formula for physiological dead space (14). CO_2 tension was converted into concentration using the oxygenated CO_2 dissociation curve. Stroke volume was calculated by cardiac output heart rate.

Statistical analysis

Cardiovascular responses were analysed using analysis of variance (ANOVA), with a log transformation to obtain normality, and with condition, subject and exercise level as independent variables. The criterion level of significance was set at $p < 0.05$. A Tukey multiple comparison test was applied to specify the differences when significant changes were found. Differences between groups were assessed using the Student's t-test. To protect against a Type-I error using repeated t-tests, an alpha of 0.01 was chosen. All data are presented as mean ± SD.

RESULTS

Characteristics of the subjects were not significantly different between TP and PR (Table I). TP showed significantly lower power output peak values during the maximal pretest than PR. This resulted in lower values for **V**O_2, **V**O_2 per kg body mass (**V**O_2/kg), ventilation and cardiac output during all submaximal exercise tests for TP compared to PR. During the sitting, supine, anti-G suit, and stockings tests heart rate and SBP were significantly lower in TP compared to PR. TPR was significantly higher in TP than in PR during all tests. Rating of perceived exertion was not significantly different between the two groups.

Physiological responses in TP and PR (n = 9)

All subjects had significantly higher **V**O_2, **V**O_2/kg, ventilation and cardiac output during arm-cranking exercise with FES compared to sitting (Table II). Heart rate was significantly lower during the supine and anti-G suit tests than during sitting alone. Exercise in the supine position, as well as with FES, induced a significant rise in

Table I. *Characteristics of subjects with tetraplegia (TP) and paraplegia (PR)*

	TP ($n = 5$)	PR ($n = 4$)
Age (years)	34 ± 9	28 ± 7
Body mass (kg)	67.8 ± 13.5	71.3 ± 10.3
Sum of skinfolds (mm)	35.5 ± 14.2	43.9 ± 20.2
Sport activity (h/wk^{-1})	2.0 ± 0.7	2.2 ± 1.0
Duration of lesion (years)	11.4 ± 8.1	7.0 ± 4.5

Table II. *Physiological responses of all subjects (n = 9) during submaximal arm-cranking exercise (mean of three levels, i.e. 20%, 40% and 60% of the maximal power output) under the five different conditions.*

VO_2 = oxygen uptake per min; $VO_2 \cdot kg^{-1}$ = oxygen uptake per kg body mass per minute; VE = ventilation per minute; Q = cardiac output; HR = heart rate; SV = stroke volume; SBP = systolic blood pressure; DBP = diastolic blood pressure; TPR = total peripheral resistance

	Sitting	Supine	Anti-G suit	Stockings	FES
VO_2 ($l.min^{-1}$)	0.71 ± 0.24	0.71 ± 0.25	0.70 ± 0.21	0.70 ± 0.21	0.86 ± 0.19**
VO_2/kg ($ml.min^{-1}.kg$)	10.2 ± 3.1	10.1 ± 3.0	10.0 ± 2.6	10.1 ± 2.8	12.2 ± 2.6**
VE ($l.min^{-1}$)	24.4 ± 7.7	22.3 ± 7.5	23.8 ± 5.5	24.1 ± 5.6	29.3 ± 8.3**
Q ($l.min^{-1}$)	10.0 ± 3.8	10.1 ± 3.9	9.5 ± 3.8	10.0 ± 2.8	11.8 ± 2.7**
HR ($beats.min^{-1}$)	103.7 ± 22.3	89.0 ± 18.0**	94.9 ± 13.7**	99.6 ± 19.3	102.4 ± 19.3
SV (ml)	97.2 ± 33.0	111.9 ± 32.0**	98.3 ± 33.4	101.4 ± 27.1	121.1 ± 28.7**
SBP (mmHg)	108.3 ± 33.5	119.6 ± 7.8**	113.7 ± 10.6**	112.3 ± 22.9	119.3 ± 16.5*
DBP (mmHg)	56.0 ± 17.6	61.7 ± 8.7*	65.3 ± 8.4**	64.5 ± 10.2	62.4 ± 6.6*
TPR ($mmHg.l.min^{-1}$)	7.3 ± 2.0	8.0 ± 3.4*	8.6 ± 2.8**	8.0 ± 1.8*	6.9 ± 1.9*

* $p < 0.05$, ** $p < 0.01$.

stroke volume. SBP was significantly higher during supine, anti-G suit, and FES testing. All conditions resulted in a significant increase in DBP. TPR rose significantly during the supine, anti-G suit, and stockings tests, whereas TPR decreased significantly during FES. None of the conditions had a significant effect on rating of perceived exertion. Because TP and PR exhibited different cardiovascular responses to exercise and treatments, the results will also be presented and discussed separately for each group.

Physiological responses in TP (n = 5)

TP demonstrated significantly higher **VO_2**, **VO_2/kg**, and ventilation during exercise with FES compared to sitting (Figs. 2 and 3). Cardiac output was significantly higher with stockings and FES. Heart rate, however, was significantly lower when exercise was performed supine, with the anti-G suit or stockings compared to sitting. Stroke volume was significantly higher during supine, stockings, and FES testing. A significant increase in SBP, DBP, and TPR was observed during supine exercise and with the anti-G suit. FES produced an increase in SBP and DBP (Fig. 4).

Physiological responses in PR (n = 4)

Compared to sitting, **VO_2** and **VO_2/kg** were significantly higher during FES whereas a significantly lower **VO_2** and **VO_2/kg** was demonstrated with the anti-G suit and stockings (Figs. 2 and 3). Despite these changes in **VO_2**, no changes in cardiac output could be observed. Heart rate was significantly lower during supine, anti-G suit, and FES testing. Only during supine exercise was a significant increase in stroke volume observed. No significant effects were observed for any of the conditions on SBP, DBP or TPR (Fig. 4).

DISCUSSION

Although both TP and PR demonstrate impaired circulatory responses to arm exercise, marked differences can be observed in the effects of the four conditions on circulatory responses between the two groups.

The supine position

This study clearly demonstrates effects of exercise in the supine position compared to the sitting position on cardiovascular responses for TP and PR. The significant decrease in heart rate and increase in stroke volume seen in all subjects in combination with an unchanged **VO_2** and cardiac output suggests an effective blood volume displacement from peripheral to the central parts of the body, resulting in an elevated end-diastolic ventricular volume and improved myocardial contraction. These findings are in agreement with previously reported results in SCI and able-bodied subjects (1, 8, 9, 21), but disagree with the findings of Hooker et al. (18).

TP had markedly different blood pressure responses compared to PR during supine exercise. Pressure changes induced by a blood volume shift may initiate baroreflexes such as vagal cardiac activity and vasodilatation in order to maintain and regulate blood pressure levels (6, 10). It can be hypothesized that these reflexes

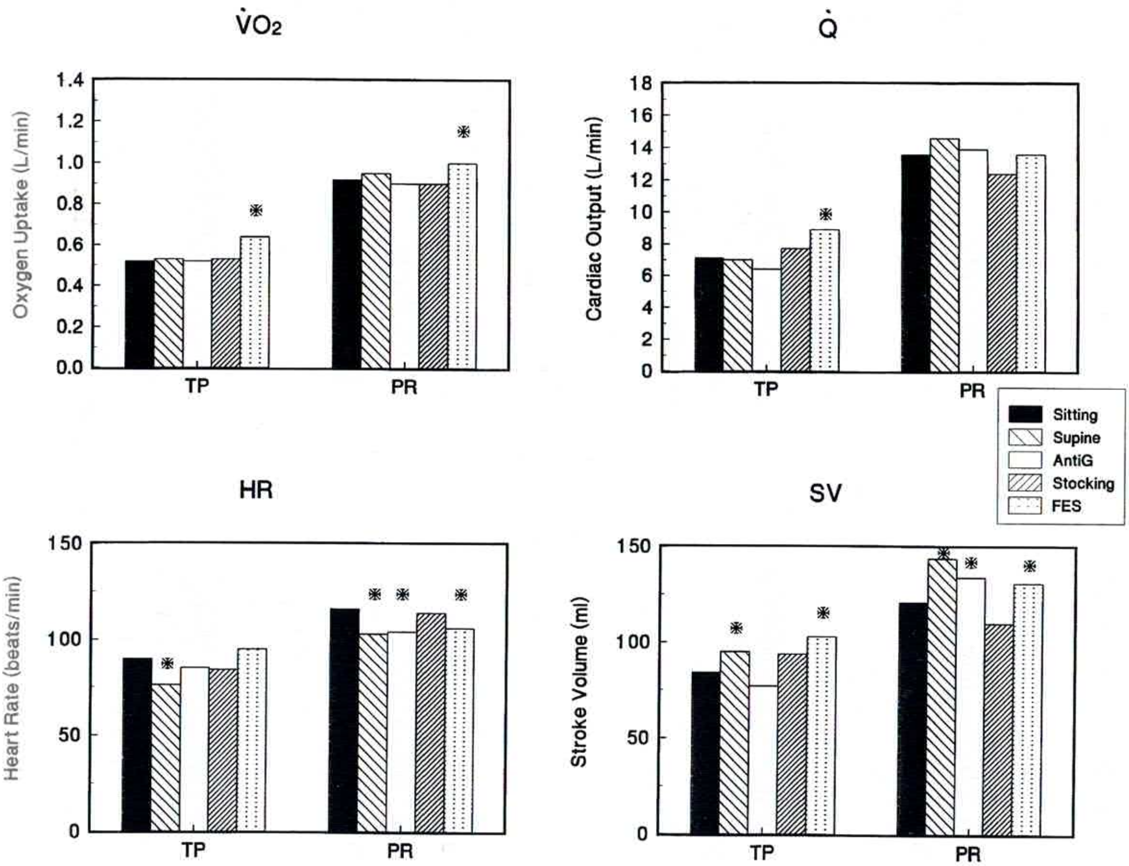

Fig. 2. Cardiac output (**Q**) in $l \cdot min^{-1}$, stroke volume (SV) in ml and heart rate (HR) in $b \cdot min^{-1}$ vs oxygen uptake (**VO_2**) in $l \cdot min^{-1}$ in individuals with tetraplegia (TP) and paraplegia (PR) during 40% of the PO peak under the five different conditions. *$p < 0.05$, significantly different from the sitting condition.

are more impaired in TP, which may explain their more pronounced response in blood pressure in the supine position compared to PR.

Previous researchers (8, 21) suggested but could not confirm that supine exercise may benefit arm-exercise economy by improved biomechanical stability of the shoulder girdle. This was not confirmed in the present study either. Neither mechanical efficiency (PO/VO_2) nor rating of perceived exertion differed significantly between the sitting and supine tests.

The anti-G suit

The observed decrease in heart rate for both groups at a given **VO_2** and cardiac output may be the result of a blood-volume displacement induced by the lower body external pressure of the anti-G suit. However, no significant increases in stroke volume were observed. Hopman et al. (12) reported similar results in a study on PR. In that study, the insignificant rise in stroke volume was explained by its variability (due to variations in cardiac output), and this may also be true for the present study. In addition, increased vagal activity as a baroreflex response may contribute to a reduction in heart rate (6). The results of the cardiovascular responses in TP are in agreement with previously reported findings by Pitetti et al. (23). The increases in SBP, DBP, and TPR with the anti-G suit in TP are in marked contrast to the lack of blood pressure changes in PR. Because of the impaired regulatory capacity for blood pressure in TP, as previously described, the pressure applied by the anti-G suit may play a pivotal role in the regulation of cardiovascular responses. Pressure was set at 55 mmHg for both groups, which may be appropriate for PR with normal resting blood pressure values. However, for TP, who typically have very low resting blood pressure values (range in DBP 34–62 mmHg), 55 mmHg may affect the venous and arterial system (10). Consequently,

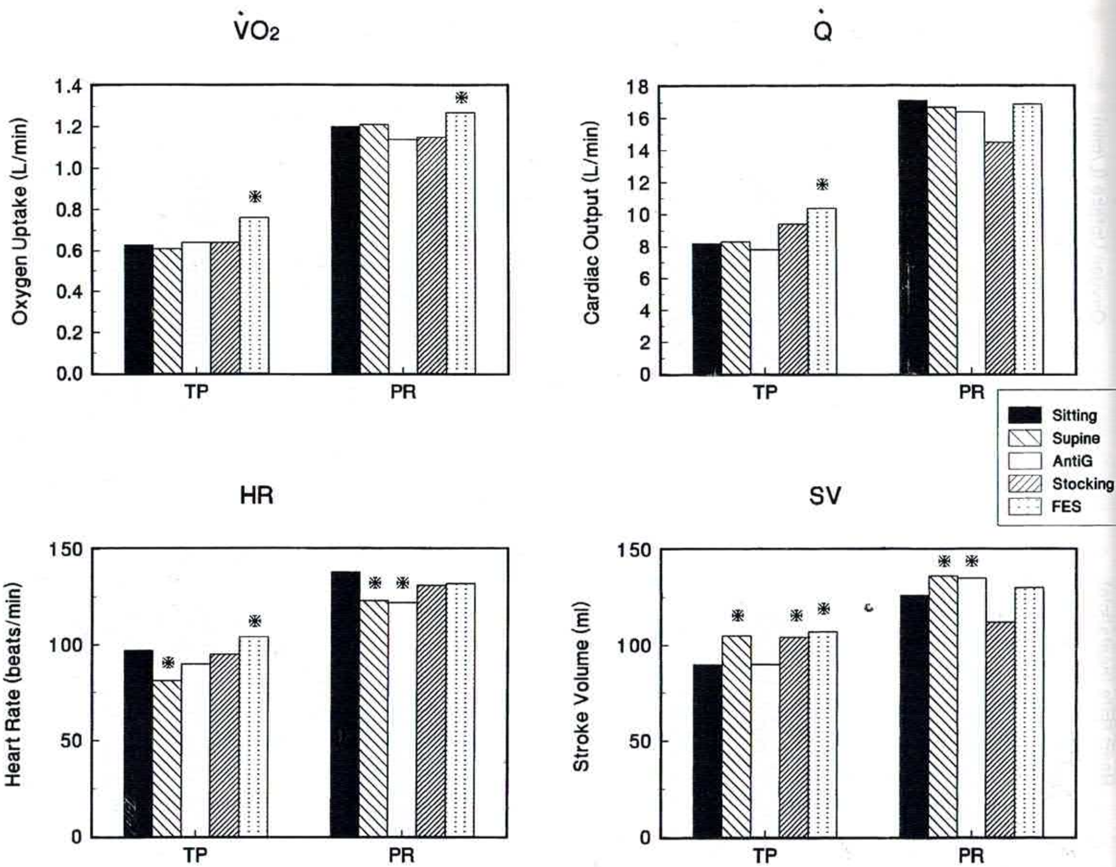

Fig. 3. Cardiac output (**Q**) in $l \cdot min^{-1}$, stroke volume (SV) in ml and heart rate (HR) in $b \cdot min^{-1}$ vs oxygen uptake (**VO_2**) in $l \cdot min^{-1}$ in individuals with tetraplegia (TP) and paraplegia (PR) during 60% of the PO peak under the five different conditions. *$p < 0.05$, significantly different from the sitting condition.

afterload may increase, which will increase end-diastolic ventricular volume and decrease stroke volume. Therefore, it is recommended that future studies adapt the pressure in the anti-G suit to about 10–20 mmHg below the individual resting DBP.

Stockings and abdominal binder

This study illustrates that stockings and binders, normally used to prevent venous stasis, post-operative deepvenous thrombosis and orthostatic hypotension during postural changes, do have an effect on cardiovascular responses during submaximal exercise. These responses are strikingly different between TP and PR. The higher stroke volume and cardiac output and lower heart rate in TP may have resulted from compression of the venous system in the lower body by the stockings and abdominal binder, resulting in a central blood volume shift. As a result, preload may have increased. Because stockings and binders exert lower pressure than the anti-G suit, afterload probably did not increase in TP as was seen at 55 mmHg using the anti-G suit. The lack of a similar response in PR is most likely the result of the relatively low pressure generated by stockings and binders, which may not influence the venous system during exercise in PR. Results suggest that stockings and abdominal binders provide hemodynamic benefits for TP (10–20 mmHg below DBP) but not for (with a higher DBP).

Functional Electrical Stimulation

The observed increases in **VO_2**, **VE**, **Q**, and stroke volume while using FES may be the result of an increase in active muscle mass, as well as the effect of FES on activation of the peripheral muscle pump. Similar results

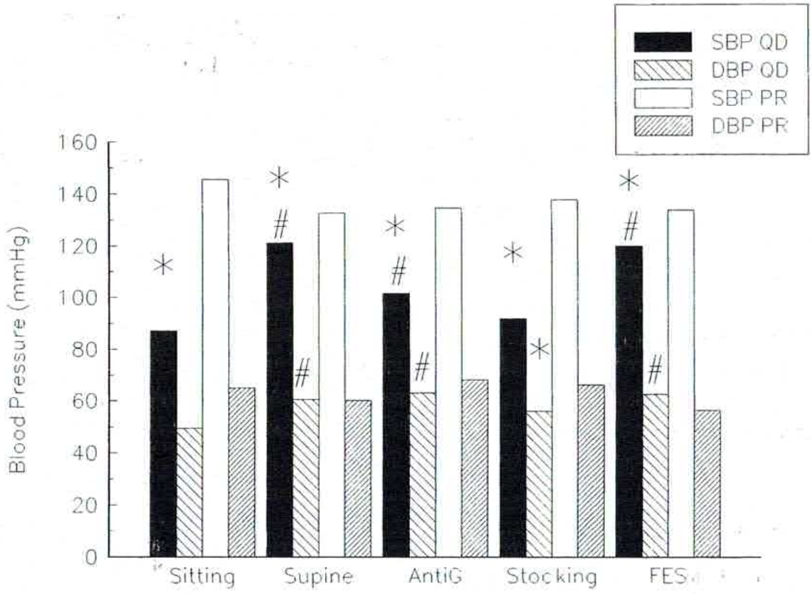

Fig. 4. Systolic blood pressure (SBP) and diastolic blood pressure (DBP) in mmHg, for individuals with tetraplegia (QD) and paraplegia (PR) during arm exercise at 60% of PO peak under the five different conditions. $^*p < 0.01$, significantly different between groups. $\#p < 0.05$, significantly different within a group compared to the sitting condition.

have been reported by other investigators; these results were explained by the fact that FES supported the redistribution of blood and enhanced EDVV during arm exercise (4, 11, 17, 22). However, a greater vasodilatation and corresponding decrease in TPR is expected to occur as more muscle mass is activated during exercise. The decline in TPR found in the present study is in agreement with Davis et al. (4) who also used a static stimulation protocol of FES during arm exercise. A lower TPR may decrease cardiac afterload and favour more complete left ventricular emptying during myocardial contraction, resulting in a greater stroke volume (24). In addition, the increased active muscle mass, as a result of adding FES to arm exercise, should enhance VO_2, and consequently cardiac output and stroke volume will rise.

Of note is the different response to FES between PR and TP. The relatively small increase in $\mathbf{VO_2}$ and blood pressure in PR compared to TP is in agreement with findings by Davis et al. (4) and Thomas et al. (25) in individuals with PR, and by Hooker et al. (17) and Figoni et al. (7) in individuals with TP. These investigators explained the differences by the different modes of stimulation (i.e. static versus dynamic) and by differences in fitness status of the subjects. The present study, however, shows that using the same FES stimulation in TP and PR with comparable fitness levels still produced different cardiovascular responses. Possible explanations for these observed differences include: (a) the relative effect of the FES-induced activation of leg muscles and the concomitant increase in $\mathbf{VO_2}$ may be greater in TP, and (b) the supporting effect of FES on the redistribution of blood may be more pronounced in TP as a result of their greater impairment.

Tetraplegics versus paraplegics

A smaller active muscle mass, greater impairment of the sympathetic nervous system and potential cardiac atrophy in TP may account for their lower exercise responses (16, 19, 26). The higher TPR in TP (TP: 10.4, 9.0, 7.6 $mmHg \cdot l \cdot min^{-1}$ and PR: 8.4, 6.2, 5.4 $mmHg \cdot l \cdot min^{-1}$, at exercise levels of 20%, 40% and 60%, respectively) may be partly explained by the small active muscle mass, and therefore the concomitant exercise-induced vasodilatation will be limited. However, the general consensus of a permanent vasodilatation below the level of the spinal cord lesion (the so-called "venous blood pooling"), caused by sympathetic decentralization and paralysed and/or flaccid musculature, would suggest a lower TPR in TP than in PR. The results of this study suggest that the vascular bed below the lesion is diminished as a functional adaptation to inactivity; this may cause the higher TPR in TP compared to PR.

Future research should be directed towards establishing an optimum adjustment of the lower body positive pressure to resting blood pressure values in individuals with SCI. Training studies using these applications are needed to elucidate the long-term effect on exercise responses and fitness levels in individuals with SCI. In addition, future studies should address the question whether these treatments would have effect on long-term circulatory adaptations in SCI individuals.

In conclusion, the results of this study indicate that supine position, the anti-G suit, stockings, and FES testing provide central hemodynamic benefits to persons with SCI during submaximal arm exercise. However, the working mechanisms of each condition are different and the effects depend on the level of the spinal cord lesion.

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