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Thermoregulatory responses of spinal cord injured and able-bodied athletes to prolonged upper body exercise and recovery

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Study design: Single trial, two factor repeated measures design.
Setting: England, Cheshire.
Objectives: To examine the thermoregulatory responses of able-bodied (AB) athletes, paraplegic (PA) athletes and a tetraplegic (TP) athlete at rest, during prolonged upper body exercise and recovery.
Methods: Exercise was performed on a Monark cycle ergometer (Ergomedic 814E) adapted for arm exercise at 60% VO_2 peak for 60 min in cool conditions ('normal' laboratory temperature; 21.5±1.7°C and 47±7.8% relative humidity). Aural and skin temperatures were continually monitored.
Results: Mean (±S.D.) peak oxygen uptake values were greater ($P<0.05$) for the AB when compared to the PA (3.45±0.45 l min^{-1} and 2.00±0.46 l min^{-1}, respectively). Peak oxygen uptake for the TP was 0.91 l min^{-1}. At rest, aural temperature was similar between groups (36.2±0.3°C, 36.3±0.3°C and 36.3°C for AB, PA and TP athletes, respectively). During exercise, aural temperature demonstrated relatively steady state values increasing by 0.6±0.4°C and 0.6±0.3°C for the AB and PA athletes, respectively. The TP athlete demonstrated a gradual rise in aural temperature throughout the exercise period of 0.9°C. Thigh skin temperature increased by 1.3±2.5°C for the AB athletes ($P<0.05$) whereas the PA athletes demonstrated little change in temperature (0.1±3.4°C and −0.7°C respectively). Calf temperature increased for the PA athletes by 1.0±3.6°C ($P<0.05$), whereas a decrease was observed for the AB athletes of −1.0±2.0°C ($P<0.05$) during the exercise period. During 30 min of passive recovery, the AB athletes demonstrated greater decreases in aural temperatures than those for the PA athletes ($P<0.05$). Aural temperature for the TP increased peaking at 5 min of recovery remaining elevated until the end of the recovery period. Fluid consumption and weight losses were similar for the AB and PA athletes (598±433 ml and 403±368 ml; 0.38±0.39 kg and 0.38±0.31 kg, respectively), whereas changes in plasma volume were greater for the AB athletes (−9.8±5.8% and 4.36±4.9%, respectively; $P<0.05$).
Conclusion: The results of this study suggest that under the experimental conditions PA athletes are at no greater thermal risk than AB athletes. A relationship between the available muscle mass for heat production and sweating capacity appears evident for the maintenance of thermal balance. During recovery from exercise, decreases in aural temperature, skin temperature and heat storage were greatest for the AB athletes with the greatest capacity for heat loss and lowest for the TP athlete with the smallest capacity for heat loss. Initial observations on one TP athlete suggest substantial thermoregulatory differences when compared to AB and PA athletes.

Keywords: paraplegia; tetraplegia; arm crank exercise; aural temperature; skin temperature; recovery

Introduction

Due to the loss of sympathetic regulation in spinal cord injury there is a reduced sweating capacity[1] and vasomotor regulation below the level of lesion.[2] Consequently, spinal cord injured subjects are considered to be at a thermoregulatory disadvantage in terms of the available cooling mechanisms and blood redistribution during exercise. However, although the combination of exercise and thermal stress pose a difficult physiological problem for the spinal cord injured population[3] relatively little is known regarding

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the thermoregulatory responses of spinal cord injured subjects during endurance exercise.

Recently, Price and Campbell[4] observed that spinal cord injured (SCI) athletes with spinal cord lesions between T3/4 and L1 were under no greater thermal strain during 90 min of exercise at 80% peak heart rate in cool conditions when compared to able-bodied (AB) athletes. Differences though in lower body thermoregulatory responses at rest, during exercise and recovery were evident. However, it was observed that a wide range of relative exercise intensities was represented at 80% peak heart rate. In a similar study, Dawson *et al*[5] employed exercise at a level of 60% peak oxygen uptake in both cool and hot conditions. Although this may be a more appropriate method of determining exercise intensity subjects numbers were small and no data concerning recovery from exercise were reported.

While there is relatively little known regarding the thermoregulatory responses of paraplegic athletes during exercise, even less information is available regarding the thermoregulatory responses of tetraplegic athletes. As these subjects demonstrate a complete loss or severely reduced sweating capacity[6,7] large increases in body temperature can occur during exercise.[8] However, Ready[9] and Gass[10] reported only small increases in rectal temperature for tetraplegic athletes during 30 min of exercise in cool conditions (21°C). The thermoregulatory responses of tetraplegic athletes to longer exercise durations have not been reported. The purpose of this study was to examine the thermoregulatory responses of paraplegic and able-bodied athletes at rest, during prolonged exercise of a fixed relative intensity and recovery. A further aim was to examine the thermoregulatory responses of a tetraplegic athlete under the same conditions.

Methods

Subjects

Twenty-one subjects volunteered to participate in this study. The group comprised of ten trained spinal cord injured (SCI) athletes and 11 trained canoeists that acted as able-bodied (AB) controls. All trained and competed regularly at a national or international level. The SCI group comprised of nine trained paraplegic athletes (PA; T3/T4-L1) and one trained tetraplegic athlete (TP; C6/C7). Further details regarding the spinal cord injured subjects are shown in Table 1. Mean age, body mass and sum of four skinfolds are shown in Table 2. Subjects attended the laboratory on two separate occasions.

Preliminary tests

To determine the work load which would elicit an exercise intensity of 60% peak oxygen uptake (VO_2 peak), all subjects performed four submaximal stages of arm crank exercise (ACE) and a test for VO_2 peak.[11] Each submaximal exercise stage was 4 min in duration and followed by a 2 min rest period in order to minimise local fatigue.[12,13] Expired air was collected during the final minute of each stage via the Douglas bag technique. Samples were analyzed for fractions of expired oxygen and carbon dioxide (Servomex Analyser Series 1400, Crowborough, England) and evacuated (Harvard Dry Gas Meter, Harvard Apparatus Ltd, Kent, England) to determine ventilation rate (VE). Values for oxygen consumption (VO_2), carbon dioxide production (VCO_2) and respiratory exchange ratio (RER) were subsequently calculated. Both analysers were calibrated before each series of measurements with nitrogen, a calibration gas and room air. On cessation of the fourth exercise stage, subjects rested for at least 5 min in order to allow heart rate to return to below 100 bts.min^{-1}. Subjects then undertook a continuous, incremental test to determine VO_2 peak. An expired air sample was obtained during the final minute of the test and a small 20 μl capillary blood sample was obtained from the earlobe for the determination of blood lactate concentration (BLa; YSI 1500 Sport Lactate Analyser, Yellow Springs Instruments, Yellow Springs, USA). Performing the submaximal exercise stages prior to the VO_2 peak test had no detrimental effect upon the peak physiological values achieved.[14] All tests were undertaken on a Monark cycle

Table 1 Characteristics of the paraplegic athletes

Subject	*Lesion level*	*Aetiology of spinal cord injury*	*Time since injury (years)*	*Sport*
1	L1	Spina Bifida	21.0	Athletics
2	T3/T4	Traumatic	10.0	Athletics
3	T12	Traumatic	16.0	Basketball
4	T8	Traumatic	35.0	Basketball
5	T12	Spina Bifida	22.0	Basketball
6	T8	Traumatic	11.5	Athletics
7	T6/T7	Traumatic	26.0	Weight Training
8	T10	Spina Bifida	22.0	Swimming
9	T12	Spina Bifida	26.0	Athletics

Table 2 Physical characteristics for the able-bodied (AB) athletes, paraplegic (PA) athletes and the tetraplegic (TP) athlete (Mean ± S.D.)

	AB athletes (n = 11)	*PA athletes* (n = 9)	*TP athlete* (n = 1)
Age years	30.3 ± 7.4	28.5 ± 4.5	24.1
Body Mass kg	78.3 ± 7.2	67.9 ± 14.0	65.6
Sum of four skinfolds mm	37.2 ± 10.1	52.7 ± 21.4	32.9

ergometer (Model 814E, Varberg, Sweden) adapted for upper body exercise. The procedure for the TP athlete was similar to that for the AB and PA athletes but employed submaximal workloads of 7, 14, 21, and 28 Watts and an incremental protocol of 7 Watts every 2 min for determination of peak oxygen uptake.

Prolonged exercise test

On the second visit to the laboratory all subjects performed 60 min of ACE at a work load set to elicit 60% VO_2 peak established from the preliminary tests. All tests were performed in normal laboratory conditions ('cool' environment; 21.5±1.7°C and 49.0±7.8% relative humidity). On arrival at the laboratory for the 60 min test, subjects rested quietly for 15 min. At the end of this period resting heart rate (HR) was recorded (Polar Sports Tester PE4000, Kempele, Finland) and a resting expired air sample was obtained. A small 20 μl capillary blood sample was obtained from the earlobe and analyzed for BLa. A 5 ml venous blood sample was obtained from the antecubital vein from which haemoglobin (Clandon HemoCue, HemoCue Ltd, Sheffield, England) and haematocrit (Hawksley Reader, Hawksley & Sons, Sussex, England) were subsequently analyzed to determine plasma volume.[15] Body mass was then recorded (Seca 710, seated scales, Hamburg, Germany) after individuals had evacuated their bladders. Skinfold measurements were taken from the biceps, triceps, subscapular and suprailiac sites using Harpenden skinfold callipers (British Indicators Ltd, Luton, England), in accordance with the procedures of Durnin and Wormersley.[16] Subjects wore lightweight tracksuit trousers, socks and training shoes.

Thermistors were positioned for measures of aural and skin temperatures. Aural temperature was measured by an aural thermistor inserted into the subjects' auditory canal[17] and securely plugged and taped in position. The external ear was then insulated with cotton wool.[18] Aural temperature was employed in the present study as rectal temperature has been considered to be inappropriate as a measure of core temperature in paraplegics during exercise[19] and subject discomfort is often reported from the use of oesophageal probes.[20,21] Skin thermistors were placed at the forehead, forearm, upper arm, back, chest, abdomen, thigh and calf in order to establish the whole body thermoregulatory response. Thermistors were attached to the skin using narrow strips of water permeable surgical tape (3M Transpore, Loughborough, England) in a criss-cross pattern. The ends of the strip were anchored with surgical tape. This technique maintained an appropriate skin-to-thermistor interface while minimising the area of skin covered by the surgical tape.[22] Subjects then undertook a standardised 5 min warm up at a work rate of 25–35W on the arm crank ergometer. Once completed subjects were allowed to undergo their usual stretching routine. Subjects then exercised at an intensity of 60% VO_2 peak for 60 min. Subjects were allowed to drink plain water *ad libitum* throughout the exercise period. On completion of the exercise test, subjects remained in the seated position and a second 5 ml venous blood sample was obtained. Post-exercise haemoglobin concentration and haematocrit were subsequently analyzed. Subjects then rested quietly for 30 min and were re-weighed.

Aural and skin temperatures were recorded at rest, post warm-up and every 5 min during the exercise period and during the first 30 min of recovery. Values were recorded by a Grant Squirrel meter logger (Grant Instruments, SQ8-16U, Cambridge, England) via Edale thermistors (Edale Instruments, Cambridge, England). One minute expired air samples were collected via the Douglas bag technique at 5, 15, 30, 45, and 60 min of exercise. Capillary blood samples were obtained from the earlobe at these time points during the exercise period and also at 5 min post-exercise. Ratings of perceived exertion (RPE, Borg Scale[23]) were also obtained during each expired air collection. Heat storage was calculated from the following formula employed by Havenith *et al*,[24] where; Heat Storage = $(0.8\ \Delta T\text{core} + 0.2\ \Delta T\text{skin})\cdot C_b$, and C_b is the specific heat capacity of the body tissue ($3.49\ J\cdot g^{-1}\cdot {}^\circ C^{-1}$). Values were calculated from changes in aural and skin temperature[25] from resting values at 5, 15, 30, 45 and 60 min of exercise, post warm-up and 15 and 30 min of the recovery period.

Statistical analysis

The peak physiological responses to incremental ACE for the AB and PA athletes were compared using independent *t*-tests. The thermoregulatory and physiological data from the prolonged exercise test were compared using two way Analysis of Variance with repeated measures. Significance was accepted at the $P < 0.05$ level. Where significance was obtained Scheffé *post-hoc* analysis was undertaken. The data for the TP athlete were described.

Results

Preliminary tests

The peak physiological responses for the PA athletes, AB athletes and the TP athlete to incremental arm crank exercise are shown in Table 3. Peak oxygen uptake (VO_2 peak), ventilation rate (VE peak) and power output (PO peak) were greater for the AB athletes when compared to the PA athletes ($P < 0.05$). Peak heart rate and BLa peak were similar. The peak physiological responses for the TP athlete were consistently lower than those observed for the PA and AB athletes.

Physiological responses during prolonged arm crank exercise

Oxygen uptake and BLa were lower for the PA athletes throughout the exercise period when compared to the AB athletes ($P<0.05$). Both groups of athletes demonstrated a peak in BLa at 15 min of exercise. There were no differences observed between HR, RER or RPE responses for the AB and PA athletes during the exercise period. The physiological responses for the TP athlete were lower than those for the PA and AB athletes throughout the exercise period.

Aural temperature at rest, during exercise and recovery

The aural temperature responses for the AB athletes, PA athletes and the TP athlete at rest, during exercise and recovery are shown in Figure 1. Aural temperature for the AB athletes, PA athletes and the TP athlete at rest were similar (36.3±0.3°C and 36.2±0.3°C and 36.3°C, respectively). No differences were noted between the aural temperature responses for the AB and PA athletes during the exercise period. Values were elevated from rest after 15 min and 20 min of exercise for the AB and PA athletes, respectively. After 30 min of exercise, relatively steady state aural temperatures were observed for both groups of athletes. At the end of the exercise period similar increases in aural temperature were observed (0.6±0.4°C and 0.6±0.3°C for the AB and PA athletes, respectively) with values remaining elevated until 5 and 10 min of recovery, respectively. During recovery from exercise, aural temperature for the PA athletes was warmer than that observed for the AB athletes ($P<0.05$). During exercise the TP athlete demonstrated a gradual increase in aural temperature of 0.9°C. This trend was not observed for any other athlete. During recovery from exercise, aural temperature for this athlete peaked at 5 min and then decreased slowly throughout the remainder of the recovery period. By the end of the recovery period the TP athlete demonstrated an elevation in aural temperature of 0.6°C above pre-exercise values.

Table 3 Peak physiological responses for the able-bodied (AB) athletes, paraplegic (PA) athletes and the tetraplegic (TP) athlete during incremental arm crank exercise (Mean±S.D.)

	AB athletes (n=11)	*PA athletes* (n=9)	*TP athlete* (n=1)
VO$_2$ peak l.min^{-1}	3.45±0.40	2.04±0.32*	0.91
VO$_2$ peak ml.kg.min^{-1}	43.0±4.7	30.5±8.2*	11.3
HR peak bts.min^{-1}	180±11	185±8	116
VE peak l.min^{-1}	111.6±16.6	74.2±16.0*	29.7
PO peak Watts	213±19	134±33*	66
BLa mmol.l^{-1}	6.40±1.09	7.10±1.37	2.88
RER peak	1.17±0.05	1.12±0.07	1.04

*Significantly different from the AB group at the $P<0.05$ level

Skin temperatures during prolonged exercise and recovery

Skin temperature responses for the AB athletes, PA athletes and the TP athlete at rest, during exercise and recovery are shown in Figures 2 and 3. Similar skin temperature responses were observed for the AB and PA athletes at the forehead and upper arm sites. Forehead, forearm, chest and abdomen demonstrated little change from resting values for either group ($P>0.05$). However, the upperarm and back sites for the AB athletes were elevated above resting levels from the end of exercise to 20 min of recovery and at the end of exercise and between 15 and 20 min of recovery, respectively ($P<0.05$). No elevations in temperature for these sites were observed for the PA athletes. Forearm skin temperature for the PA athletes was warmer than that observed for the AB athletes throughout the exercise period ($P<0.05$). Thigh skin temperature for the AB athletes was warmer than that observed for the PA athletes from 15 min of exercise until 45 min of exercise ($P<0.05$). At the end of the exercise period thigh skin temperature had increased by 1.1±2.5°C and 0.1±3.4°C for the AB and PA athletes, respectively. Thigh skin temperature for the AB athletes decreased between 15 and 30 min of recovery when compared to values at the end of exercise ($P<0.05$). No change was observed for the PA athletes. Thigh skin temperature for the TP athlete

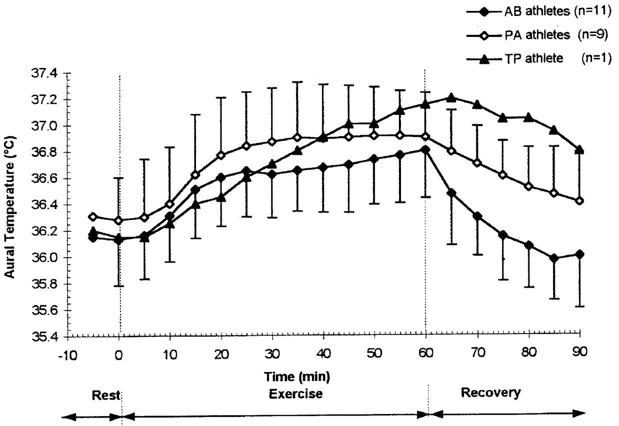

Figure 1 Aural temperature for able-bodied (AB) athletes, paraplegic (PA) athletes and a tetraplegic (TP) athlete at rest, during prolonged arm crank exercise, and recovery

demonstrated a similar response to that observed for the PA athletes.

Calf skin temperature for the AB athletes tended to decrease during the exercise period (-0.9 ± 2.0°C) whereas an increase in calf skin temperature of 1.0 ± 3.4°C was observed for the PA athletes. During the initial 30 min of recovery a further decrease in calf skin temperature was observed for the AB athletes when compared to rest (-3.6°C ± 1.3; $P<0.05$), whereas a gradual decrease to resting levels was observed for the PA athletes. When the change in calf skin temperature was compared to resting values, cooler calf skin temperatures were observed for the AB athletes from 30–45 min of exercise and throughout the recovery period when compared to the PA athletes ($P<0.05$). The TP athlete demonstrated little change in calf skin temperature from resting values throughout exercise or recovery.

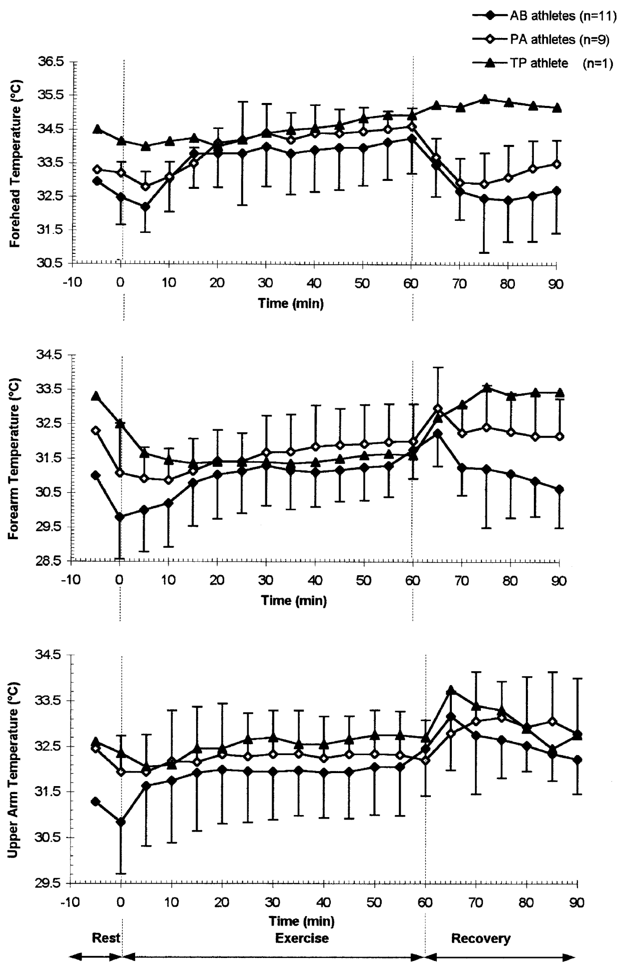

Figure 2 Forehead, forearm and upper arm skin temperatures for able-bodied (AB) athletes, paraplegic (PA) athletes and a tetraplegic (TP) athlete at rest, during prolonged arm crank exercise, and recovery

Heat storage

Heat storage for the AB athletes, PA athletes and the TP athlete during exercise and recovery is shown in Figure 4. After 15 min of exercise, heat storage was elevated above values post warm-up for both the AB (1.26 ± 0.93 J.g^{-1}; $P<0.05$) and PA athletes (0.44 ± 0.57 J.g^{-1}; $P<0.05$). Values for the AB athletes tended to be greater than those for the PA athletes at the end of exercise (2.40 ± 1.08 J.g^{-1} and 1.81 ± 1.43 J.g^{-1}, respectively). During recovery from exercise heat storage decreased to -0.61 and ± 0.94 J.g^{-1} and 0.22 ± 1.18 J.g^{-1} for the AB and PA athletes, respectively. Heat storage at the end of exercise for the TP athlete increased to 2.44 J.g^{-1}, decreasing slowly to 1.05 J.g^{-1} at the end of the recovery period.

Fluid balance

Weight loss, fluid intake and total weight loss during exercise were similar for the AB and PA athletes (-0.38 ± 0.39 kg and -0.38 ± 0.31 kg; 598 ± 433 ml and 403 ± 368 ml; 0.99 ± 0.35 kg and 0.78 ± 0.28 kg, respectively). Plasma volume changes during exercise were greater for the AB athletes when compared to the PA athletes (-9.80 ± 5.80% and -4.36 ± 4.94%, respectively; $P<0.05$). The TP athlete demonstrated a small change in body weight and plasma volume

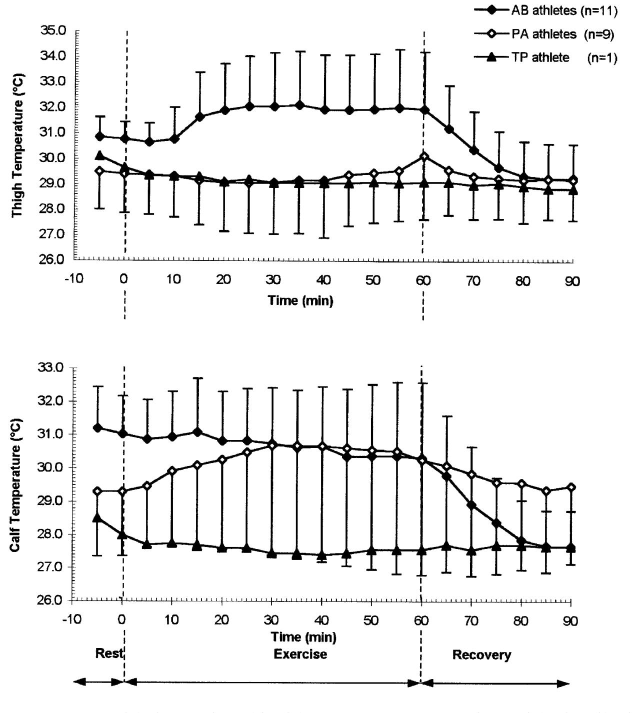

Figure 3 Thigh and calf skin temperatures for able-bodied (AB) athletes, paraplegic (PA) athletes and a tetraplegic (TP) athlete at rest, during prolonged arm crank exercise, and recovery

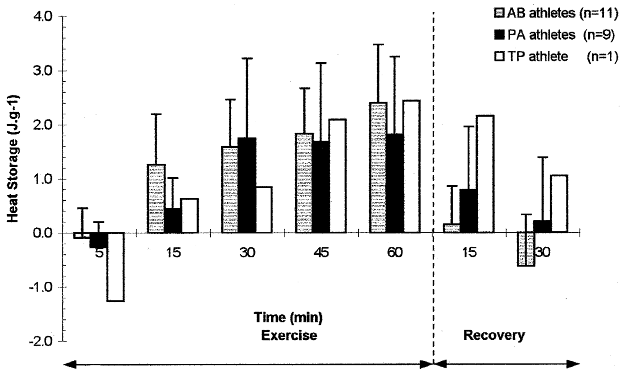

Figure 4 Heat storage for able-bodied (AB) athletes, paraplegic (PA) athletes and a tetraplegic (TP) athlete at rest, during prolonged arm crank exercise and recovery

(0.1 kg and −0.89%, respectively) and consumed no fluid during the exercise period.

Discussion

Physiological responses

The lower VO_2 peak values for the able-bodied (AB) athletes when compared to the paraplegic (PA) athletes are consistent with previous comparisons of AB and PA athletes of similar training status.[4,5] The lower values for the PA athletes when compared to the AB are considered to be due to the reduced muscle mass and sympathetic nervous activity below the level of spinal cord injury.[2,26] The lower peak heart rate for the TP athlete is also consistent with previous studies and considered to be due to the high level of spinal cord transection and reduced sympathetic innervation to the heart.[27]

During prolonged exercise all athletes were working at similar percentages of VO_2 peak with decreases in BLa and RER being indicative of steady state aerobic exercise.

Aural temperature at rest

At rest, no differences were observed between aural temperature values for the AB athletes, PA athletes and the TP athlete. Previous studies have reported lower resting core temperatures and a wider range of resting core temperatures for spinal cord injured subjects when compared to able-bodied subjects.[28,29,30] This has been suggested to be due to a reduction in basal metabolic rate and heat production below the level of spinal cord injury.[30,31] The differences in core temperature between AB and SCI subjects observed by these authors were suggested to represent a change in set-point of the thermoregulatory system. However, this is not supported by the results of the present study.

Aural temperature during exercise

No differences were observed between the aural temperature responses of the AB and PA athletes during exercise. Increases in aural temperature were consistent with those reported previously for oesophageal, rectal and aural temperature of AB and PA athletes during exercise of a similar intensity and duration.[4,19,32,33] Furthermore, the relatively steady state aural temperatures after the initial 30 min of exercise for both the AB and PA groups suggests that there was a balance between the heat production and heat loss mechanisms. For PA athletes this may be due to the reduction in sweating capacity being matched by a reduction in available muscle mass for heat production. The results of the present study are therefore consistent with previous studies in suggesting that trained PA athletes, with a range of spinal cord injuries, are able to regulate body temperature as well as able-bodied subjects during prolonged exercise in cool conditions.[4]

Skin temperatures during exercise

Changes in skin temperatures were similar to previous studies.[4] The increase in thigh skin temperature and decrease in calf skin temperature for the AB athletes suggests an important role of the lower limb for heat dissipation and blood redistribution, respectively. Little change in thigh skin temperature for the PA athletes may demonstrate the loss of vasomotor control and reduced metabolic heat production whereas the increase in calf skin temperature was probably due to the reduced blood redistribution and decreased sweating capacity within the lower limb and consequent heat storage. Such heat storage may also contribute to the similar increase in aural temperature for the PA athletes and AB athletes even though the absolute metabolic rate representing 60% VO_2 peak is lower for the PA group.[4]

Aural and skin temperatures during recovery from exercise

During recovery from exercise aural temperature was greater for the PA athletes when compared to the AB athletes. This was also reflected in the heat storage values. It is possible that the reduced evaporative heat loss of the lower body of the PA athletes and an inability to dissipate the metabolic heat stored during the exercise period resulted in heat being retained during recovery from exercise. The temperature of the circulating blood may then be maintained resulting in an elevated aural temperature. The greater heat storage for spinal cord injured athletes during recovery from exercise, when compared to the able-bodied, may be of importance in the treatment of exercise induced hyperthermia in wheelchair athletes.

During recovery from exercise the decreases in skin temperature were greatest for the AB athletes, in particular, the large decrease in calf skin temperature.

This decrease has previously been suggested to be due to a local hypothermic response post exercise.[4] In contrast, the slower decrease in calf skin temperature for the PA athletes suggests a passive dissipation of heat from the lower body to a relatively cool environment and the loss of vasomotor responses.

Fluid balance

The AB athletes demonstrated a greater change in plasma volume during exercise when compared to the PA athletes. Total weight losses and fluid consumption also tended to be greater for the AB athletes. These results may reflect the area of sensate skin available for sweating and consequently, body fluid losses. A large surface area available for sweating, such as for the AB athletes, would enable greater fluid losses to occur when compared to the reduced surface area for sweating of the PA athletes. Due to the absence of sweating and evaporative fluid losses for the TP athlete, little change in plasma volume occurred during exercise. Changes in plasma volume during exercise may therefore be related to the area of sensate skin and consequently, the level of spinal cord lesion.[26]

Although weight losses tended to be smaller for the PA athletes, they were not statistically different from those reported for the AB athletes. Similar weight losses from a reduced surface area for sweating may indicate a greater sweat output from the available sweat glands of the PA athletes. This would be consistent with previous suggestions of a thermoregulatory adaptation of the sensate skin sweating capacity.[4] However, for the same sweat losses the PA athletes demonstrated smaller changes in plasma volume. Specific studies of fluid balance and sweat output may therefore be useful in determining any differences in fluid shifts of AB and PA athletes during exercise.

Thermoregulatory responses for the TP athlete

The balance between heat production and heat loss for the AB and PA athletes during exercise was not observed for the TP athlete. Even though the active muscle mass and metabolic heat production for this athlete was much lower than observed for the PA and AB athletes (2.45 Kcal.min^{-1}, 5.88 Kcal.min^{-1} and 9.84 Kcal.min^{-1} at 5 min of exercise, respectively) this could not be balanced during exercise on the complete absence of sweating. However, whether this imbalance between heat production and heat loss mechanisms occurs for tetraplegic subjects only or whether it also exists for paraplegics with high level thoracic spinal cord transection, who possess a greater reduction in sweating capacity than subjects with low level spinal cord injuries, could not be determined from the results of the present study.

The TP athlete demonstrated little change in calf or thigh skin temperatures during exercise. This may indicate that little or no peripheral heat storage occurred due to a greater degree of atrophy of the vasomotor system with higher level spinal cord injuries[34,35] and reduced convective heat flow from the body core to the periphery. Consequently, more central heat storage may have occurred as was evident in the continual increase in aural temperature. The central heat storage was also evident from the peak in aural temperature at 5 min of recovery and consistent with the observations of Gass *et al.*[10] These results are consistent with previous findings suggesting that the heat generated during exercise in cool conditions is not a major source of thermal stress for tetraplegic athletes.[9,10]

Training status

All athletes completed the exercise duration without any thermal discomfort. This may be due not only to the absence of an external heat load but also to the fact that all athletes were trained. This is particularly interesting for the TP athlete who, with no sweating capacity, would not demonstrate any partial acclimatisation from training manifested in sudomotor mechanisms.

In conclusion, the results of this study suggest that under the conditions studied, AB athletes and the PA athletes are under a similar thermal strain. A relationship between the available muscle mass for heat production and sweating capacity for the AB and PA athletes appeared to be evident in the maintenance of thermal balance. During recovery from exercise, the decrease in aural temperature, skin temperature and heat storage appeared to be greatest for the AB athletes with the greatest capacity for heat loss and lowest for the TP athlete with the smallest capacity for heat loss. The initial observations of one TP athlete suggest a thermoregulatory imbalance during exercise and recovery with substantial differences in thermoregulation when compared to other athletes with spinal cord injury.

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