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Cutaneous Vascular Response and Thermoregulation in Individuals With Paraplegia During Sustained Arm-Cranking Exercise

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This study investigated whether a 60-minute arm-cranking exercise at 50% of the individual maximal power output would increase lower limb skin blood flow (laser Doppler flowmetry) in individuals with high-level (T5–T9; n = 6) and low-level paraplegia (T10–T12; n = 6), compared to 6 able-bodied controls. Significant ($P < 0.05$) group by time interactions (two-way repeated measures ANOVA) were found for leg cutaneous vascular conductance, leg skin temperature and esophageal temperature. Cutaneous vascular conductance increased to a peak of ~180% of pre-exercise rest in both paraplegic groups and to ~436% in the control group, with differences after 15, 30, 45 and 60 minutes of exercise. Leg skin temperature increased by ~0.3 °C in individuals with paraplegia and decreased by ~2.0 °C in able-bodied. Esophageal temperature increases at the end of exercise were higher in individuals with paraplegia (~0.9 °C) than in able-bodied subjects (~0.5 °C). Heart rate was higher in the paraplegic groups than in able-bodied, whilst stroke volume and cardiac output were not different (impedance cardiography). The data suggest that lesion level had no influence on the results. These findings indicate that there is no excessive shunting of blood to the skin of the lower limbs of individuals with paraplegia during sustained exercise.

Key words: Spinal cord injury, laser Doppler flowmetry, active cutaneous vasodilation, esophageal temperature, skin temperature.

Introduction

A spinal cord injury (SCI) generates a number of disadvantages with respect to the thermoregulatory function of the human body. This derives from the damage to the autonomic nervous system which affects both sweating and the ability to vasoregulate the peripheral vasculature [14]. When exposed to passive heating, persons with a SCI show a reduced active vasodilation in sensate body parts [3], as well as an overall reduced sweat production, with little increase in regional sweat rates below the spinal lesion level [3,15]. As a consequence, their body core temperature tends to rise to higher levels than in able-bodied (AB) [15], a phenomenon probably proportional to the level of the spinal lesion [5].

Similar observations have been made in persons with SCI during exercise-induced metabolic heat production [2,15]. The AB subject adapts to such a situation by an active cutaneous vasodilation and sweat response, to favour dry and evaporative heat losses, respectively, and to minimize the rise in body core temperature [10]. In persons with SCI, however, subnormal sweat responses have been observed, with minimal sweating below the spinal lesion [6,15], although core temperature increases more compared to AB subjects performing at the same exercise intensity [2,15].

The functional role of the peripheral cutaneous vasoregulation in individuals with paraplegia has been hardly addressed so far [12,13]. It has been speculated that during exercise skin blood flow is increased in persons with SCI to optimize the temperature gradient between skin and the environment and to enhance dry heat exchange [2,18], in compensation for their impaired sudomotor function. This might help explain the cardiovascular drift (a decrease in cardiac stroke volume [SV] with a concomitant rise in heart rate [HR]) and the decrease in cardiac output (Q) which may be observed in SCI individuals during prolonged exercise sessions or performance in thermally strenuous conditions [1,2,6].

The speculations of a higher skin blood flow to compensate for a deficient evaporative heat loss are essentially based on the observation that lower limb skin temperature (T_{sk}) of individuals with paraplegia tends to increase during exercise [1,2,4]. Changes in T_{sk} may, however, not reflect accurately changes in skin blood flow, since T_{sk} is also influenced by other, opposite factors, like sweat evaporation and an increased

blood temperature through progressive heat storage during exercise [16].

The main purpose of this study was to investigate leg cutaneous vascular responses and thermoregulatory function during exercise in individuals with different levels of paraplegia and in AB controls. The hypothesis was to test if prolonged submaximal arm-cranking exercise would induce an increased shunting of blood to the insensate skin in individuals with paraplegia as compared to AB. Cardiovascular parameters were assessed concomitantly, because of their important adjustments to the thermoregulatory processes.

Methods

Subjects

Twelve individuals with paraplegia and 6 AB controls participated in the present study which was approved by the Faculty Ethical Committee. They were previously fully informed about the purpose and the implications of participation, and written informed consent was obtained from all subjects. The spinal lesions of the individuals with paraplegia were complete and of traumatic, longstanding origin (Table 1). The sympathetic innervation of the lower limbs, achieved by nerve fibers emerging from the spine between T10 and L2, was taken as a basis to subdivide the individuals with paraplegia into two groups. The first group comprised 6 individuals with "low-level"-paraplegia (LP), with spinal lesions between T10 and T12. The second group comprised 6 individuals with "high-level"-paraplegia who had lesions between T5 and T9 and no central sympathetic control in the lower limbs. Subjects with lesions above T5 were not admitted to the study, to avoid influences of an impaired sympathetic innervation to the heart or to the upper limbs. None of the subjects were undergoing medical treatment at the time of participation in the experiments.

Table 1 Physical characteristics (means $\pm$ SD) of the three subject groups studied

	AB	LP	HP
Age (yr)	28.3 $\pm$ 5.6	31.3 $\pm$ 8.3	32.2 $\pm$ 7.0
BM (kg)	78.7 $\pm$ 10.1	60.2 $\pm$ 11.2*	82.0 $\pm$ 10.7
Height (m)	1.80 $\pm$ 0.08	1.74 $\pm$ 0.10	1.81 $\pm$ 0.07
TSI (yr)	–	8.4 $\pm$ 6.5	12.7 $\pm$ 6.4
PO _{max} (W)	110.0 $\pm$ 7.8	110.0 $\pm$ 22.6	97.5 $\pm$ 20.7

BM = body mass, TSI = time since injury, PO_{max} = maximal power output, AB = able-bodied, LP = individuals with low-level paraplegia, HP = individuals with high-level paraplegia; *significantly different from the two other groups ($P < 0.05$)

Protocol

The subjects visited the laboratory twice. During their first visit they performed a continuous incremental arm-cranking exercise until volitional fatigue. Initial power output (PO) was 15 W and PO was increased by 15 W every 3 minutes, the total duration of the test varying between 15 and 27 minutes. On the second occasion they underwent a continuous 60-minute

arm-cranking exercise trial at 50% of their individual maximal PO achieved in the first test (PO_{max}). The subjects were instructed to pedal the crank at a frequency of 60 rpm. All had refrained from caffeine, alcohol and nicotine for a minimum of 8 hours prior to the experiments. Upon arriving at the laboratory, the participants changed into shorts to prevent restriction of convective and evaporative cooling from the skin during exercise. They were then prepared for the experiments and rested for 30 minutes in a wheelchair in the exercising position. All the tests were performed in the morning, in a room where ambient temperature was 23 ± 2 °C and relative humidity was 53 ± 3 % (means $\pm$ SD).

Materials and measurements

The arm crank ergometer used was a modified electro-magnetic Rodby cycle ergometer. The axis was put at shoulder height of the seated subject, at a distance which allowed for a slight elbow flexion at the point of maximal pedal excursion. For all subjects both feet were suspended in special footholders, with the knees bent at about 30° in relation to the horizontal line, to minimize the influence of gravity on leg blood flow and to avoid lower limb muscle contractions in AB.

During the tests, metabolic measurements (minute ventilation, oxygen and carbon dioxide concentrations of expired air) were continuously monitored, using open-circuit spirometry. A computerized Siemens ELEMA spirometer (Erlangen, Germany) provided values integrated over time intervals of 30 seconds. Expired ventilation was measured with a pneumotachograph, and the O₂ and CO₂ concentrations were assessed with an Oxymat-M paramagnetic O₂ analyzer and an Ultra-mat-M infrared CO₂ analyzer, respectively. Both analysers were calibrated before each test with a reference gas of known concentrations (15.9% O₂, 5% CO₂). The parameters thus determined were expired minute ventilation (VE, l $\times$ min⁻¹, STPD), oxygen consumption ($\dot{V}O_2$, l $\times$ min⁻¹, STPD) and carbon dioxide production ($\dot{V}CO_2$, l $\times$ min⁻¹, STPD).

Central hemodynamics were evaluated by impedance cardiography, using a Minnesota Impedance Cardiograph (model 304b, Instrumentation for Medicine Inc., Greenwich, USA) and a tetrapolar aluminum band electrode configuration (Cardiograph Electrode Tape, IFM). The first time derivative of trans-thoracic impedance changes, dZ/dt, and the ECG were registered on a personal computer via a 16-bit analogue-to-digital data acquisition card (AT-MIO-16XE-50, National Instruments, Austin, USA), using a sample frequency of 300 Hz. Custom-made software was used to perform off-line filtering and ensemble-averaging of the dZ/dt curve and to calculate cardiac SV and HR [21]. When using this method in the present conditions, the random variation for SV was evaluated at 8.9% and the test-retest correlation was 0.86, based on $n = 9$ subjects. Q (l $\times$ min⁻¹) was taken as the product of SV and HR. All metabolic and central hemodynamic parameters were determined over periods of 30 seconds at rest and at 15, 30, 45 and 60 minutes of exercise.

Leg skin blood flow was evaluated using LDF. This technique is based on the relationship between cutaneous blood flow and the frequency shift in laser light when applied to the skin, thus providing a reliable index of the relative variations in skin blood flow [8]. The measurements are not influenced by un-

derlying muscle blood flow [9], since the measurement depth is limited to more or less 1 mm. In the present study, the Periflux 4001 Master (Perimed AB, Stockholm, Sweden) was used. It had a 1 mW diode laser (780 nm) and its bandwidth allowed for Doppler shift measurements between 20 Hz and 25 kHz. The signal recorded was represented by an arbitrary value (perfusion unit - PU), resulting from the number of blood cells moving in the measuring volume multiplied by the mean velocity of the cells. The instrument was calibrated on a daily basis to the two measuring points 0 PU and 250 PU using the PF1001 Motility Standard.

Two integrating probes were used, transmitting/receiving light to/from 7 different scattering volumes simultaneously. This results in a seven-fold increase of the measuring volume with respect to standard LDF probes, over an area of about 1 cm², and a significant decrease in the average intrasubject coefficient of variation [17]. Each probe was inserted into a heating probe holder (PF 450 Thermostat Probe Holder) applied to the skin by means of a double-sided adhesive ring. The heater unit (PF 4005 PeriTemp Heater, Perimed AB, Stockholm, Sweden) to which the probe holders were connected maintained local skin at 39°C, a commonly used temperature to standardize and facilitate investigations of skin blood flow changes without abolishing reflex cutaneous vasoconstriction [19] or vasodilation [20]. Measurements were performed on the left leg, on the middle of the tibialis anterior muscle and on the middle of the triceps surae muscle. These skin sites were previously shaved and cleaned with alcohol. A personal computer recorded the LDF signal continuously with a frequency of 1 Hz. Biological zero, i.e., the persisting low LDF signal during vascular occlusion, was registered after 20 minutes of pre-exercise rest. A pressure cuff applied proximally to the LDF probes, just below the left knee, was rapidly inflated to over 200 mm Hg for 2 minutes. The stable value read during the last 30 seconds was taken as biological zero and subtracted from all other LDF readings [17]. The values thus obtained from the two probes were averaged and expressed with respect to the mean value over 2 minutes at the end of the 30-minute rest period, since LDF allows for semi-quantitative measurements only. The LDF recordings were considered over 1-minute intervals to account for minor temporal variations in skin blood flow. During the tests, the left foot of the subject was immobilized laterally between two vertical bars, and the fiber optic cables of the LDF probes were carefully secured to the nearest solid object to avoid movement artifacts in the LDF signal during arm-cranking exercise.

Arterial blood pressure was measured noninvasively at the posterior tibial artery of the right ankle using an electrophygmomanometer (6004 NIBP Monitor, BCI International). Measurements were performed at rest and continuously throughout the exercise test. The average time interval between two consecutive measurements was 46 seconds. Mean arterial pressure was calculated as diastolic pressure + 1/3 pulse pressure. An index of cutaneous vascular conductance (CVC) was calculated as skin blood flow divided by mean arterial pressure, using an interpolated value of mean arterial pressure, and expressed as a percentage of preexercise control value [20].

Esophageal temperature (T_{es}) was measured as an index of body core temperature of the subjects [4]. An esophageal tem-

perature probe (YSI Model 402, 2.5 mm diameter) was inserted through a nostril to a depth determined on the basis of individual sitting height: probe depth (cm) = $0.479 \times$ sitting height (cm) + 4.44. This equation ($n=20$, $r^2=0.86$) has been established based on radiographical analyses, to optimize the placement of a probe, at the level T8/9, relatively distant from major conducting airways and proximal to the left ventricle and the aorta [11]. Leg T_{sk} was recorded as the average from two sites, just next to the two LDF probes at a distance of approximately 5 cm. The skin temperature probes (YSI Model 409) were attached by porous tape (Transpore surgical tape, 3M) with a small capacity for heat storage. T_{es} and T_{sk} were recorded every 5 seconds and stored in a computer file via the same data acquisition board as the one used for the impedance measurements. As for the LDF measurements, the values considered were average values over 1 minute.

Statistics

Between-group differences were evaluated using one-factor analyses of variance (ANOVA) and the Student-Newman-Keuls post-hoc test when statistical significance was reached. Two-way ANOVA procedures for repeated measures were applied to investigate group by time interactions of all parameters at rest, 15, 30, 45 and 60 minutes of exercise. Significance was accepted at the $P < 0.05$ level. Data are presented as means $\pm$ standard deviations.

Results

Arm exercise performance

The three groups under study were relatively well-matched with respect to their physical characteristics, except for body mass which was lower in LP (Table 1). During the second sub-maximal test performed at 50% of PO_{max} , the absolute PO was 56.7 ± 2.6 , 55.8 ± 11.1 and 50.0 ± 11.0 W for AB, LP and HP, respectively. These values were not significantly different from each other. After 15 minutes of exercise, $\dot{V}O_2$ had increased to 1.3 ± 0.1 , 1.2 ± 0.2 and 1.2 ± 0.1 l $\times$ min⁻¹ in AB, LP and HP, respectively, and remained relatively stable throughout the test.

Cutaneous vasculature

There was a significant group by time interaction for CVC ($F = 5.960$, $P < 0.001$), the average values for AB reaching significantly higher levels (peak average of 436%) than those registered in both SCI groups (peak average of 214% and 156% for LP and HP, respectively). The results obtained for skin blood flow were similar to those for CVC in all three groups (data not shown). No differences were found between the two paraplegic groups.

Temperature regulation

Pre-exercise T_{sk} was similar in all three groups, but T_{es} at rest was significantly lower in HP subjects ($36.89 \pm 0.13^\circ\text{C}$) compared to AB ($37.30 \pm 0.16^\circ\text{C}$), with intermediate values found for LP ($37.07 \pm 0.32^\circ\text{C}$). Due to differences at rest, the variations in temperature measurements with respect to rest: values (ΔT_{sk} and ΔT_{es}) were used for further processing, rather than absolute values. A significant group by time interaction was obtained for ΔT_{sk} ($F = 20.955$; $P < 0.001$). The values found at the end

Table 2 Summary of central hemodynamic parameters registered at rest, 15, 30, 45 and 60 minutes of arm-cranking exercise at a constant workload of 50 % of individual maximal power output (means $\pm$ SD)

		rest	15 min	30 min	45 min	60 min
HR (bpm)	AB	69.4 $\pm$ 11.0	114.5 $\pm$ 13.3	118.1 $\pm$ 13.5	120.3 $\pm$ 15.6	116.3 $\pm$ 12.9
	LP	90.0 $\pm$ 10.6*§	142.1 $\pm$ 15.8*	147.2 $\pm$ 16.8*	150.8 $\pm$ 16.3*	149.8 $\pm$ 21.3*
	HP	72.9 $\pm$ 11.4	132.4 $\pm$ 9.2*	140.4 $\pm$ 9.4*	140.9 $\pm$ 11.7*	137.7 $\pm$ 10.9*
SV (ml $\times$ b ⁻¹)	AB	99 $\pm$ 23	104 $\pm$ 17	101 $\pm$ 18	97 $\pm$ 24	102 $\pm$ 21
	LP	91 $\pm$ 12	82 $\pm$ 13	78 $\pm$ 17	75 $\pm$ 15	78 $\pm$ 10
	HP	97 $\pm$ 31	87 $\pm$ 20	83 $\pm$ 14	86 $\pm$ 19	89 $\pm$ 20
Q (l $\times$ min)	AB	6.7 $\pm$ 1.0	11.8 $\pm$ 1.8	11.8 $\pm$ 1.5	11.4 $\pm$ 2.2	11.6 $\pm$ 1.6
	LP	8.3 $\pm$ 1.8	11.7 $\pm$ 2.0	11.5 $\pm$ 2.6	11.4 $\pm$ 2.6	11.7 $\pm$ 2.0
	HP	6.9 $\pm$ 2.0	11.4 $\pm$ 2.1	11.6 $\pm$ 1.4	12.1 $\pm$ 2.1	12.1 $\pm$ 2.1

HR = heart rate, SV = stroke volume, Q = cardiac output, AB = able-bodied, LP = individuals with low-level paraplegia, HP = individuals with high-level paraplegia; *significantly different from AB, § significantly different from HP ($P < 0.05$)

of exercise were -1.99 ± 0.52 °C for AB, 0.22 ± 0.22 °C for LP and 0.41 ± 0.89 °C for HP. A significant group by time interaction was also observed for ΔT_{es} ($F = 2.607$; $P = 0.021$), AB showing overall smaller increases in T_{es} than the individuals with paraplegia. After 60 minutes of exercise, ΔT_{es} was higher in LP (0.80 ± 0.39 °C) and HP (0.85 ± 0.14 °C) compared to AB (0.48 ± 0.23 °C). There were never significant differences between LP and HP for these parameters.

Central hemodynamics

Primary parameters related to central hemodynamics (HR and SV) were determined by ensemble-averaging of the recorded impedance cardiograms, using a series of cardiac cycles which showed limited artefact distortion. Thus, in 90 % of the cases, the calculations were based on 15 cardiac cycles or more, with a minimum number of 7 cycles used. At rest HR was higher in LP compared to HP and AB (Table 2). During exercise, significantly higher HR values were found in both LP and HP with respect to AB. No differences were found for SV and Q between the groups, either at rest or during exercise.

Discussion

Cutaneous vascular responses

The main purpose of the present investigation was to analyse and compare leg cutaneous vascular responses and thermoregulation between AB, LP and HP during submaximal arm-cranking exercise. Increased lower limb skin blood flow has been hypothesized as a mechanism used in SCI subjects to favour dry heat exchange [2, 18]. It has been speculated that such an adaptation would compensate for a less efficient sweat function and diminished evaporative cooling, and that it could explain the generally higher cardiac strain encountered by individuals with paraplegia. The present findings indicate that increased leg CVC (and skin blood flow) is not a key mechanism of the thermoregulatory function of SCI persons with longstanding complete lesions between T5 and T12. On the contrary, the cutaneous vasodilation observed in AB was much higher than that found in both SCI groups (Fig. 1, upper panel).

The results of this study are well in accordance with the observations of Muraki et al. [12, 13], who reported that thigh skin blood flow did not rise markedly in persons with lesions above T12 during exercise. Active cutaneous vasodilation is normally triggered by a rise of body core temperature beyond a certain threshold. It is controlled by nonadrenergic pathways of the sympathetic nervous system, involving a transmitter which is not known to date [7]. In SCI subjects, the vasomotor and sudomotor responses are probably dependent on the lower-most intact part of the sympathetic chain [14]. Thus, the reason why leg CVC in the individuals with paraplegia did not increase to comparable levels as in AB was probably due to the deficit of sympathetic control in this area. As a consequence, persons with a SCI endure a thermoregulatory disadvantage, as reflected by their higher ΔT_{es} values noted here (Fig. 1, lower panel). The greater thermoregulatory strain encountered may also be due to a reduced effector response in sensate areas, as suggested by the results of Freund et al. [3]. They found that passive heating induced a smaller active vasodilation in the forearm of individuals with paraplegia compared to AB. Freund et al. [3] speculated that the blunted vascular response in sensate body areas could be the consequence of a deficit in afferent information from thermosensitive sites within the spinal cord or other deep tissues below the lesion, associated with a proportional deficit in effector activity. However, in the present study, the exercise-induced thermal strain was of endogenous origin, and the question of a smaller effector response in sensate body regions during exercise would require experimental verification.

Influence of the lesion level

The CVC responses were similar in both LP and HP, although the definition of the two groups was based on the neurological injury level (cf. above). This excludes an influence of the lesion level in the individuals tested here. It was expected that the CVC of LP would parallel that of AB, which might have been the case in the more proximal thigh regions, as previously described [12, 13]. Thus, the present results suggest that the sympathetic impairment in the analysed leg region was similar in both paraplegic groups. Another possibility is that LP had higher plasma catecholamine responses through their intact innervation of the adrenal medulla, as opposed to HP. Increased lev-

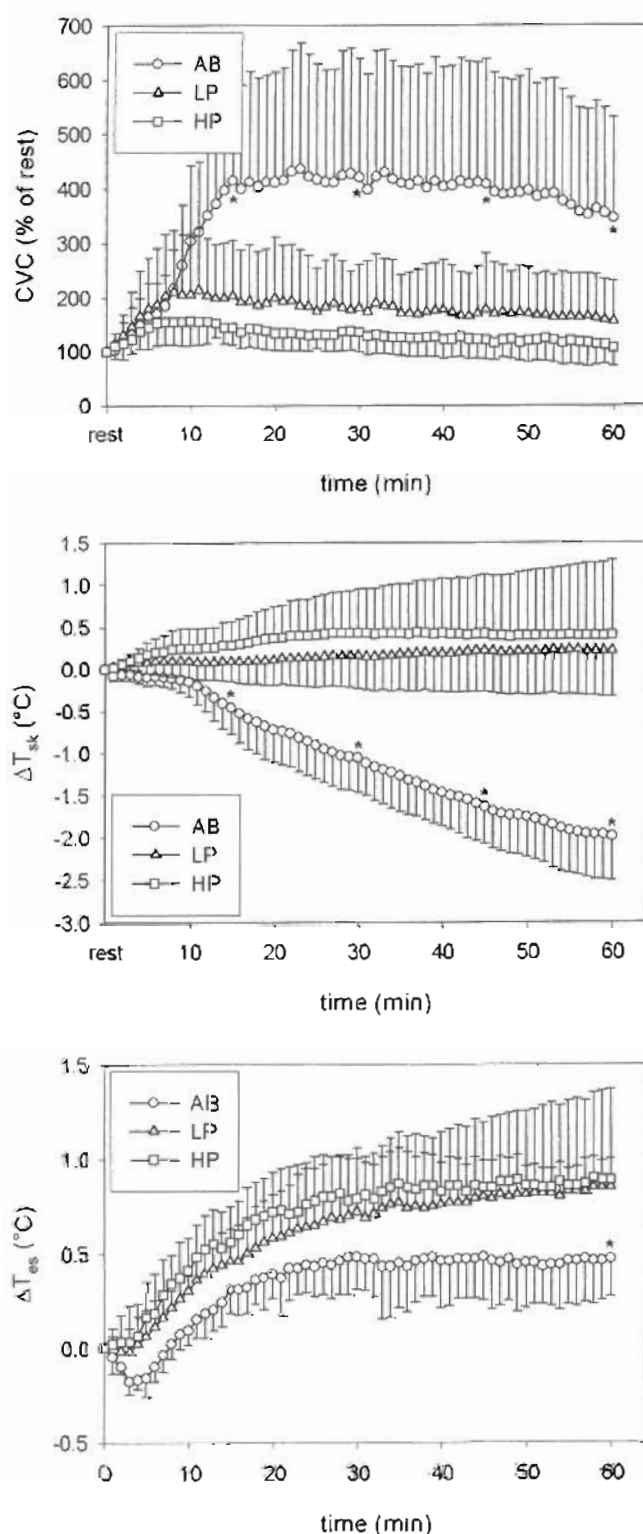


Fig. 1 Variations of cutaneous vascular conductance (CVC) (upper panel), leg skin temperature changes (ΔT_{sk}) (middle panel) and esophageal temperature changes (ΔT_{es}) (lower panel) with respect to pre-exercise rest during 60-minute arm-cranking exercise at a constant workload of 50% of individual maximal power output (means $\pm$ SD); *able-bodied (AB) significantly different from individuals with low-level (LP) and high-level paraplegia (HP) ($P < 0.05$).

els of catecholamines might have blunted the CVC responses in LP. These speculations cannot be supported by the present results and would need to be further investigated.

Temperature regulation

The thermoregulatory impairment in the individuals with paraplegia was also illustrated by the changes in T_{sk} (Fig. 1, middle panel). Although sweat rates were not analysed here, the decrease in T_{sk} in AB suggests that their sweat response was appropriate to allow for an effective evaporative cooling in the lower limbs. In LP and HP, however, leg T_{sk} showed slight increases, which may reflect an impaired sweat function with limited functional value. Again, the lesion level did not have an influence on the results. The present observations on T_{sk} are consistent with those made previously by other investigators during prolonged arm crank [1, 16] and wheelchair ergometry [2]. As to the reasons why T_{sk} of the lower limbs tends to increase in individuals with paraplegia, a number of authors have pointed out the possibility of a higher blood flow confined to the skin [1, 2, 4, 18]. Nevertheless, this explanation is unlikely in view of the results of this study. Indeed, in AB, decreases in T_{sk} were accompanied by increases in CVC and skin blood flow, and the slightly higher average T_{sk} in the HP, compared to LP, was associated with slightly lower CVC and skin blood flow values than in LP. Therefore, it seems hazardous to interpret T_{sk} changes in terms of variations in cutaneous blood flow. A more likely explanation to the leg T_{sk} rises in persons with SCI is a progressive heat storage, as a result of increasing blood temperature during exercise and the lack of dry and evaporative heat dissipation [16].

The T_{es} increase in both paraplegic groups during exercise was more pronounced than in AB (Fig. 1, lower panel), thus indicating the higher thermal stress encountered. This observation is consistent with previous findings based on oral [2] and aural temperature measurements [15, 16]. In the present study, the higher ΔT_{es} values in individuals with paraplegia might be explained, to some extent, by their somewhat lower T_{es} at pre-exercise rest, but probably also by their impaired vasomotor and sudomotor function, as discussed above.

Central hemodynamics

The evaluation of parameters related to cardiac performance revealed a higher cardiac strain encountered by the individuals with paraplegia during exercise (Table 2). HR was systematically higher in both the LP and HP compared to AB, whereas SV was slightly lower, without being significantly so. As a result, Q was always very similar in the three groups.

Absolute values found for HR, SV and Q are well in agreement with those found by Hopman et al. [6] in comparable conditions, based on the CO_2 rebreathing method. This highlights the cardiac disadvantage experienced by individuals with paraplegia compared to AB [2, 6]. In opposition to assumptions put forward by other investigators (cf. above), the higher cardiac strain evidenced in individuals with paraplegia can probably not be attributed to an excessive shunting of blood to the skin of the lower limbs, as shown by the present results.

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