Effects of two cooling strategies on thermoregulatory responses of tetraplegic athletes during repeated intermittent exercise in the heat

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Webborn, N., M. J. Price, P. C. Castle, and V. L. Goosey-Tolfrey. Effects of two cooling strategies on thermoregulatory responses of tetraplegic athletes during repeated intermittent exercise in the heat. J Appl Physiol 98: 2101–2107, 2005. First published January 27, 2005; doi:10.1152/japplphysiol.00784.2004.—Athletes with spinal cord injury (SCI), and in particular tetraplegia, have an increased risk of heat strain and consequently heat illness relative to able-bodied individuals. Strategies that reduce the heat strain during exercise in a hot environment may reduce the risk of heat illness. To test the hypotheses that precooling or cooling during intermittent sprint exercise in a heated environment would attenuate the rise in core temperature in tetraplegic athletes, eight male subjects with SCI (lesions C5–C7; 2 incomplete lesions) undertook four heat stress trials (32.0 ± 0.1°C, 50 ± 0.1% relative humidity). After assessment of baseline thermoregulatory responses at rest for 80 min, subjects performed three intermittent sprint protocols for 28 min. All trials were undertaken on an arm crank ergometer and involved a no-cooling control (Con), 20 min of precooling (Pre), or cooling during exercise (Dur). Trials were administered in a randomized order. After the intermittent sprint protocols, mean core temperature was higher during Con (37.3 ± 0.3°C) compared with Pre and Dur (36.5 ± 0.6°C and 37.0 ± 0.5°C, respectively; P < 0.01). Moreover, perceived exertion was lower during Pre (13 ± 2; P < 0.01) and Dur (12 ± 1; P < 0.01) compared with Con (14 ± 2). These results suggest that both precooling and cooling during intermittent sprint exercise in the heat reduces thermal strain in tetraplegic athletes. The cooling strategies also appear to show reduced perceived exertion at equivalent time points, which may translate into improved functional capacity.

Spinal cord injury; core temperature; thermal strain; functional capacity

Spinal cord injury results in reduced vasomotor and sweating responses below the level of lesion with subsequent thermoregulatory dysfunction (12). Studies of paraplegic individuals at rest and during exercise have shown that thermoregulatory responses are proportional to the level of lesion, reflecting the amount of sympathetic nervous system available for sweating and blood redistribution (12, 22, 26). However, when the level of spinal cord lesion is in the cervical region resulting in tetraplegia (also known as quadriplegia), much greater thermal strain is observed during both resting and exercise heat exposure (12, 26). For example, during resting heat exposure, tetraplegic individuals demonstrate the greatest increases in core temperature compared with paraplegic individuals, who in turn demonstrate greater increases than able-bodied subjects (12). During exercise in hot conditions, similar responses are also observed with tetraplegic individuals being under a much greater thermal strain than paraplegic individuals (22, 25) because of the level of lesion being above the sympathetic outflow, resulting in the absence or severe reduction of sweating capacity (12). Furthermore, during exercise in the heat, paraplegic athletes demonstrate similar increase in core temperature compared with able-bodied bodied athletes during arm crank ergometry (25) but at a much lower metabolic rate, reflecting the decreased heat dissipation. The spinal cord-injured population, especially those individuals with tetraplegia, may therefore be considered to be at greater risk from heat-related illness than able-bodied individuals.

Within the literature regarding human thermoregulation during exercise, a range of cooling strategies has been examined (17). Such studies have been undertaken to determine methods of reducing increases in body temperature during both lower body (3, 7) and upper body exercise (27, 33) in hot conditions as well as sports-specific environments (20). Techniques have involved cooling before exercise (precooling), to delay increases in body temperature (20), or cooling during exercise, to enhance the dissipation of heat gained from metabolic and/or environmental sources (27). Although tetraplegic individuals are known to be at greater risk of heat injury and that the main contributor to heat strain in tetraplegic individuals is suggested to be gains in heat from the environment (2, 26), little is known regarding the reduction of heat strain in this population. When spinal cord-injured subjects are cooled at rest, tetraplegic individuals demonstrate greater decreases in core temperature than paraplegic individuals and the able-bodied because of the lack of sympathetically induced vasoconstriction and an inability to generate large amounts of metabolic heat from shivering as a result of paralysis (5, 6, 12). It is possible that the absence of heat retaining mechanisms in tetraplegic individuals may enable a given cooling stimulus to be more effective than for paraplegic and able-bodied subjects and would have a significant impact on the reduction of heat injury in this population as well as improving the quality of life.

To the authors’ knowledge, only two studies have addressed the topic of cooling strategies in the spinal cord injured (2, 13), with both employing cooling strategies during exercise. Armstrong et al. (2) examined the effects of an ice-packet vest and a refrigerated headpiece on 5-km performance time in a group of wheelchair racers (including 4 paraplegic individuals and 1 tetraplegic individual). Although both cooling methods tended

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to show cooler rectal, skin, and mean body temperatures, no significant differences were observed between trials. The authors concluded that local cooling was ineffective because heat storage, although reduced, was not prevented. Hagobian et al. (13) examined the use of a foot-cooling device in a group of spinal cord-injured men (C5 to T3) during exercise in hot conditions. Foot cooling was successful in attenuating the rise in core temperature during exercise (1.0 ± 0.2°C) compared with a no-cooling control (1.6 ± 0.2°C). Although these studies have provided useful insights into the use of potential cooling strategies during exercise in the spinal cord injured, subjects were not athletes and the exercise employed was of an aerobic nature. These conditions do not necessarily reflect the intermittent- and high-intensity nature of many wheelchair sports and represent exercise conditions that need to be addressed. Furthermore, no study has yet reported the use of cooling strategies in a large and homogenous group of tetraplegic individuals. Therefore, the aim of this study was to describe the effects of precooling and cooling on the responses during several intermittent high-intensity exercise bouts over 28 min in tetraplegic individuals. It was hypothesized that precooling would delay the onset of increases in body temperature, whereas cooling during exercise would offset gains in heat during exercise.

METHODS

Subjects. Eight male wheelchair athletes (aged between 25 and 35 yr; 71.6 ± 10.8 kg) volunteered to participate in the study after being informed of the experimental procedures, which were approved by the University Ethics Committee. Subjects were tetraplegic athletes (C5/ C6-C7/ C8; 2 incomplete lesions), all being able to use their arms during wheelchair propulsion but with impaired use of their hands. All subjects trained and competed regularly in wheelchair tennis (n = 4) and rugby (n = 4) at either the national or international level and were familiar with arm-crank exercise. Subjects visited the laboratory on four separate occasions. During the first visit to the laboratory, anthropometric measurements were taken [sum of 4 skinfolds; Harpenden Instruments, West Sussex, UK, as described by Durnin and Womersley (9)] followed by a force velocity test and an incremental arm-crank test to volitional exhaustion. After 2-h chaperoned rest, subjects also undertook an 80-min resting heat exposure. The remaining visits involved intermittent exercise protocols with three different cooling procedures.

Instrumentation. Exercise testing was performed on a modified cycle ergometer (Ergomedic 620, Monark, Varberg, Sweden) adapted for upper body exercise that allowed athletes to remain in their everyday wheelchairs for testing. Because subjects demonstrated impaired hand function, assistance in gripping the hand cranks was provided via tape where necessary. Power measuring cranks (SRM, Welldorf, Germany) were fitted to the ergometer to record power output continuously at a sampling rate of 0.5 Hz.

Physiological measures. Subjects ingested the telemetry pill (HQ Palmetto, Fl) for the measurement of core body temperature, 8.0 ± 2.3°C before each testing condition, in accordance with Sparling et al. (30) to ensure reliable values. The telemetry pill detects surrounding temperature and transmits a temperature variable signal via short electromagnetic waves to a hand held recorder. This technology has been deemed reliable during hyperthermia (21) and has demonstrated good response times to detect temperature change by Mittal et al. (19).

Body mass in minimal clothing was determined before and after testing for an indication of nonurine fluid loss. Thermistors (Grant Instruments, Cambridge, UK) were positioned for measures of skin temperature at standard positions (28) on the chest, upper arm, thigh, and calf. Values were recorded by a Grant Squirrel meter logger (1000 Series, Grant Instruments, Cambridge, UK). Heart rate was continuously monitored (Polar Sports Tester, Kempele, Finland). Subjective measures for rating of perceived exertion (4) and thermal sensation (31) were also recorded.

Baseline measures were recorded after a 15-min period to allow stabilization of thermistors. During the 20-min precooling maneuver and time-matched period for the control and during conditions, all variables were recorded at 2-min intervals. For logistical reasons, during the intermittent sprint protocol, all variables were recorded at 1 min of each 2-min exercise block to gauge the responses during the active recovery section of the protocol. Power output was measured continuously. Peak power output during each 5-s sprint was recorded as the highest single value during each 5-s sprint. Mean work done for each 5-s sprint was calculated from the highest 3-s average for mean power output during each sprint. On completion of each intermittent sprint protocol, when subjects felt they could no longer continue, or the safety limit of a high core temperature was reached (39.3°C or a 2°C increase from rest), the trial was terminated.

Mean skin temperature was calculated using the formula of Ramathan (28), and heat storage was calculated using the formula of Havenith et al. (15): Heat storage = (0.8ΔTcore + 0.2ΔMST) · Cb, where Cb is the specific heat capacity of the body tissue (3.49 J·g⁻¹°C⁻¹). Values were calculated from changes in telemetry pill core temperature (ΔTcore) and mean skin temperature (ΔMST) from resting values at the end of the precooling maneuver and the end of the intermittent sprint protocol.

Experimental procedure. Subsequent to medical screening by a physician, all subjects refrained from vigorous exercise, caffeine, and alcohol for 24 h before reporting to the laboratory for the first time. Before all testing protocols, subjects provided a urine sample for the assessment of hydration status via urine specific gravity [Cambur10 Test, Roche Diagnostics, Mannheim, Germany (1)].

The force-velocity test consisted of three maximum-effort sprints of 5-s duration against a resistance of 2, 3, and 4% of body mass. Sprints were interspersed by 5-min active recovery on the unloaded ergometer. The resistance that yielded the highest peak power output was then used during subsequent tests. After 15-min rest, subjects were engaged in a continuous incremental exercise test to determine peak oxygen uptake (VO₂peak). This test involved increases in workload of 5 W every 2 min from an initial workload of 35 W at a cadence of 60 rpm. Expired air was collected during the last minute of each stage by using the Douglas bag technique and analyzed for oxygen and carbon dioxide content (Servomex, Crowborough, UK) and expired volume (Harvard Dry Gas Meter, Scientific and Research Instruments, Kent, UK). Heart rate was continually monitored after the VO₂peak test and 2-h chaperoned rest, subjects rested in an environmental chamber with the ambient temperature and relative humidity set at 32.0 ± 0.1°C, and 50.0 ± 1.1%, respectively, for 80 min to assess baseline thermoregulatory responses and the level of heat strain.

All exercise tests undertaken during the three remaining laboratory visits occurred inside the environmental chamber on separate days and in a randomized order. The environmental conditions were the same as for the resting heat exposure. Trials were conducted at the same time of day to negate circadian variation (16) and consisted of a repeated-measures design where subjects served as their own controls. The three trials were consisted of an intermittent sprint protocol with no cooling (Con); an intermittent sprint protocol preceded by a 20-min precooling maneuver (Pre) in which subjects wore a commercially available ice vest (Arctic Heat Products) covering the torso before exercise only; and an intermittent sprint protocol with subjects wearing the ice vest during the warm-up and intermittent sprint protocol only (Dur). The warm-up before each trial consisted of arm crank exercise at ~50% peak power output from the VO₂peak test (60 rpm, 29–37 W).

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The ice vest was frozen overnight before testing in a −20°C freezer and weighed 1.4 kg. Before baseline measures being recorded in all conditions, subjects rested for 15 min in temperate conditions (20.0 ± 0.1°C and 45.0 ± 0.1% relative humidity). For the Con condition, subjects remained resting in the same conditions for a further 20 min before entering the environmental chamber. For the Pre condition after the baseline period, subjects wore the ice vest for 20 min, after which the subjects removed the vest and entered the environmental chamber. For the Dur condition, once baseline measures had been recorded, subjects rested for 20 min as in Con before putting on the ice vest and immediately entering the environmental chamber. The intermittent sprint protocol involved fourteen 2-min exercise periods, each consisting of a 10-s passive rest, a 5-s maximal sprint from a stationary start against the optimal resistance from the force-velocity test, and 105 s of active recovery at 35% VO2 peak. No fluid intake was permitted during any of the testing. Subjects wore lightweight track-suit trousers and training shoes for all tests. The use of a 28-min intermittent sprint protocol was analyzed by using a two-way ANOVA with repeated measures (condition × time). Significance was accepted at the P < 0.05 level. Where significance was obtained, Tukey’s honestly significant difference post hoc test was undertaken. All data were analyzed by using a standard statistical package (SPSS Version 11.0) and are reported as means ± SE.

RESULTS

The physiological parameters obtained from both the force-velocity and peak aerobic arm ergometry are presented in Table 1. These values were found to be consistent with those previously reported (26) and unpublished data from other researchers using the SRM power crank device.

During 80 min of passive rest in hot conditions, core body temperature increased from resting values (36.8 ± 0.1°C) to 37.3 ± 0.1°C (P < 0.01). Mean skin temperature also increased from 32.0 ± 0.2°C at the start of the rest period to 34.8 ± 0.2°C by the end of the 80-min period (P < 0.01). By 28 min of exposure (a time period comparable to the intermittent sprint duration), heat storage was 1.06 ± 0.5 J/g. Mean heart rate was 65 ± 2 beats/min and did not change throughout the 80-min rest. Body mass was not reduced from baseline values during rest in the heat.

Precooling maneuver. The precooling maneuver reduced core temperature from rest (36.6 ± 0.1°C) by 0.3 ± 0.1°C (P < 0.05; Fig. 1) and mean skin temperature by 1.7 ± 0.4°C (P < 0.01; Fig. 2). Heat storage after the precooling period was −2.53 ± 0.35 J/g. Heart rate was not changed during precooling, although ratings of thermal sensation were lowered from rest (3.5 ± 0.4) by 20 min of precooling (1.5 ± 0.2; P < 0.01; Fig. 3). No differences were observed for any variables during the time-matched period of precooling for Con or Dur.

Table 1. Physiological characteristics of the wheelchair athletes

<table>
<thead>
<tr>
<th>Subject</th>
<th>BM, kg</th>
<th>SS, mm</th>
<th>PPO, W</th>
<th>Aerobic PPO, W</th>
<th>VO2 peak, l/min</th>
<th>HRpeak, beats/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean ± SE</td>
<td>71.6 ± 3.8</td>
<td>57.7 ± 4.1</td>
<td>220 ± 22</td>
<td>70 ± 5</td>
<td>0.96 ± 0.06</td>
<td>142 ± 4</td>
</tr>
<tr>
<td>Maximum</td>
<td>92.5</td>
<td>71.6</td>
<td>307</td>
<td>85</td>
<td>1.18</td>
<td>168</td>
</tr>
<tr>
<td>Minimum</td>
<td>57.0</td>
<td>37.1</td>
<td>134</td>
<td>49</td>
<td>0.66</td>
<td>115</td>
</tr>
</tbody>
</table>

Values are for 8 subjects. BM, body mass; SS, sum of 4 skinfolds; PPO, peak power output from force-velocity test; Aerobic PPO, PPO from the incremental test; VO2 peak, peak oxygen uptake; HRpeak, peak heart rate.
time-matched data points during the intermittent sprint protocol, mean skin temperature for Pre and Dur conditions were lower for Con \( (P < 0.01) \). Furthermore, each data point for the Dur condition was lower than Pre throughout the intermittent sprint protocol \( (P < 0.01) \). Individual skin temperatures increased from resting values during each intermittent sprint protocol trial \( (P < 0.05) \). Both thigh and calf skin temperatures were cooler than chest and arm skin temperatures at rest, after warm-up, and throughout the three intermittent sprint protocol trials.

Heat storage during the intermittent sprint protocol was not different between Con \( (3.62 \pm 0.4 \) J/g), Pre \( (4.17 \pm 0.4 \) J/g), and Dur \( (3.15 \pm 0.35 \) J/g; \( P = 0.39 \)). Heart rate increased from minute 1 to minute 13 \( (P < 0.05) \) during each intermittent sprint protocol and was not different across conditions. Change in body mass was not different between Con \( (0.15 \pm 0.1 \) kg), Pre \( (0.01 \pm 0.3 \) kg), and Dur \( (0.05 \pm 0.0 \) kg; \( P = 0.71 \)).

For the Dur condition, thermal sensation was lower \( (5.0 \pm 0.2 \) than Con \( (6.0 \pm 0.2 \), main effect; \( P < 0.05 \)) but not different from Pre \( (5.5 \pm 0.2 \); Fig. 3). Compared with values at 1 min, thermal sensation was elevated for the Con and Pre conditions \( (5.0 \pm 0.2 \) and \( 4.5 \pm 0.2 \), respectively) at 13 min \( (6.0 \pm 0.2 \) and \( 5.5 \pm 0.4 \), respectively; \( P < 0.01 \)). However, for the Dur condition, a significant increase did not occur until 15 min \( (5.5 \pm 0.4 \) from 1 min \( (4.5 \pm 0.4 \), \( P < 0.01 \); Fig. 3). Ratings of perceived exertion were lower during Pre \( (13.0 \pm 0.7 \), \( P < 0.01 \); Fig. 4) and Dur \( (12.0 \pm 0.4 \), \( P < 0.01 \); Fig. 4) compared with Con \( (14.0 \pm 0.7 \). During the intermittent sprint protocol, significant increases in perceived exertion were observed at 11 min for Con, 13 min for Pre, and 15 min for Dur. From 18 min onward, values were lower for Dur than Con \( (P < 0.01 \); Fig. 4). No significant differences were seen across conditions for overall mean work done.

**DISCUSSION**

The aim of this study was to examine the effects of precooling and cooling during intermittent high-intensity exercise in tetraplegic individuals. Physiological and thermoregulatory responses supported the use of both cooling strategies in offsetting thermal strain during 28 min of exercise.

Before any exercise trials, each subject’s thermal strain was assessed during a resting heat exposure over a comparable duration to the exercise trials in the present study and a previous study of spinal cord-injured individuals \( (26) \). Over the entire 80-min duration, core temperature, as measured via the telemetry pill, increased by \( \sim 0.5^\circ\text{C} \) with a corresponding increase in mean skin temperature of 2.4°C. The increase in core temperature was less than observed by previous studies of the spinal cord injured employing oral, aural, and rectal temperature \( (12, 29, 32 \) and probably reflects not only the greater environmental temperature of previous exposures \( (35–38^\circ\text{C} \) but also the trained nature of the subject group, which may elicit improvements in heat tolerance \( (26) \). Furthermore, no change in body mass was observed during the exposure demonstrating the lack of sweating capacity within the group.

The precooling maneuver at rest in the cool environment effectively reduced core temperature before the warm-up period. However, this was not as extreme as whole body cooling techniques such as immersion \( (18) \) or a 60-min cold shower \( (7) \), which have been employed with able-bodied subjects but are less practical for most sporting situations. The present study reduced mean skin temperature by \( \sim 1.5^\circ\text{C} \), whereas a similar technique employing able-bodied athletes over a shorter duration in a warm environment \( (30^\circ\text{C} \) reported a reduction in mean skin temperature by over 4°C and tympanic temperature \( \text{(infrared method) by} 0.9^\circ\text{C} \). It is possible that able-bodied subjects in warm conditions would have had a much greater stimulus for vasodilation from the neurologically intact whole body skin surface area. This would result in a much greater stimulus for increased cutaneous blood flow overriding any local vasoconstrictor stimulus from the relatively small surface area cooled by the ice vest. Consequently, blood would still flow through the cooled skin areas, returning to the central circulation. It is likely that this would not occur for tetraplegic subjects in the present study because of the lack of a large vasodilatory stimulus from the majority of the skin.
surface to drive blood through the cooled cutaneous circulation. When a similar ice vest to the one in the present study was employed for just 5 min after warm-up, little change in rectal or mean skin temperature was observed (8), demonstrating that the duration of cooling may have been too short even for able-bodied subjects to benefit. These differences in cooling potential are also possibly due to the greater surface area cooled (20) and the use of the Ramanathan mean skin temperature formula (28), possibly masking any local cooling effect (27). Interestingly, in the present study, chest temperature was decreased, on average, ~4°C, which is consistent with that observed by Myler et al. (20). However, although precooling was effective in the tetraplegic athletes studied, the reduction in body temperature during Pre would not be large enough to offset the gain in heat during the 80-min resting heat exposure.

During the warm-up period, heat storage during the two cooling trials was similar and ~65% of that observed for Con. This suggests that the effectiveness of the precooling strategy was maintained at a similar level as wearing the ice vest during warm-up. Although this represents only a short duration of time, such a time factor may be important for competitive situations or where limited time for cooling athletes is available. Consequently, subjects began the exercise protocol with the same body heat content for the Pre and Dur trials.

During exercise, core temperature was lower during both cooling trials compared with the no-cooling control. Furthermore, for a given time point, core temperature was lower during Pre compared with Dur, suggesting that precooling reduced the absolute increase in core temperature. However, the rate of increase in core temperature was slower for Dur compared with Pre and Con, which were similar. As a result, similar core temperatures were observed at the end of exercise for both cooling protocols. Consequently, precooling offset the absolute increase in core temperature, whereas wearing the ice vest during exercise reduced the gain in core temperature and may be due to the following. In the absence of sympathetically induced vasoconstriction, cutaneous blood would not be directed to the body core during Pre until the warm-up and

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**Fig. 2.** Mean skin temperature during the precooling maneuver, warm-up, and intermittent sprint protocol for the Con, Pre, and Dur conditions in a hot, humid environment. *a* Significant difference between Con and Pre, $P < 0.05$. *b* Significant difference between Con and Dur, $P < 0.05$. *c* Significant difference between Pre and Dur, $P < 0.05$.

**Fig. 3.** Thermal sensation scores during the precooling maneuver, warm-up, and intermittent sprint protocol for the Con, Pre, and Dur conditions in a hot, humid environment. *a* Significant difference between Con and Pre, $P < 0.05$. *b* Significant difference between Pre and Dur, $P < 0.05$. *c* Significant difference from rest, $P < 0.05$. 
exercise protocol began elevating heart rate to drive the cooled cutaneous blood to the central circulation, thus maintaining a cool core. This process would likely continue during exercise and heat exposure until skin temperature increased to a level where cutaneous blood no longer remained cool. Conversely, wearing the ice vest during exercise would enable blood returning to the central circulation from the skin to be continually cooled, thus preventing the rapid rate of increase in core temperature observed for Con. What must be considered, however, is how long the ice vest remains cold and how long the precooled skin takes to rewarm. These factors may be of importance in determining the duration of exercise capacity in this population. It is anticipated though, that in conditions of greater environmental stress the effectiveness of both strategies would be reduced.

Skin temperature demonstrated similar responses during each trial to those observed for core temperature. However, in the Dur trial, a slower increase in temperature was demonstrated during exercise, and in the Pre trial, a systematic decrease was demonstrated due to the direct application of the cooling stimuli. Considering the core and skin temperature responses combined, the Pre strategy demonstrated central cooling and offset the subsequent gain in core temperature during exercise, whereas the Dur protocol initially demonstrated peripheral cooling, facilitating direct heat transfer from the body core to the periphery. As regards heat flow, regional differences are likely to have occurred. For example, in all trials, the arms, not covered by the ice vest, reached skin temperatures similar to those of core temperature, subsequently retarding heat loss from the core to the periphery. Lower body skin temperatures of the thigh and calf, which were the coolest of any site at rest (28.5 and 26°C, respectively), increased to environmental temperature (31–32°C) during exercise, which would allow heat flow from the core to periphery and possible dry heat exchange to the environment.

The heat stored during Con represents both the metabolic heat production and that gained from the environment. Compared with the 28-min point during the resting exposure, it appears that two-thirds of the heat gained during Con was from metabolic heat production rather than the environment. If the exercise had been of a more aerobic nature, the majority of heat gained by the individuals may well have been from environmental sources, which would be consistent with previous studies involving tetraplegic athletes (2, 11). Consequently, the aim of cooling in this population during high-intensity intermittent exercise may shift toward offsetting gains in core temperature of metabolic origin. Further studies examining intermittent sprint type activities would therefore be of interest. It must be emphasized though that the group studied were trained athletes and may demonstrate an increased heat tolerance from regular increases in body temperature during training (26). Sedentary or less-trained tetraplegic subjects may well be at a greater risk of heat injury than those studied. This is further illustrated when considering that the amount of heat stored during Con was similar to that gained during 60 min of continuous exercise in similar conditions for able-bodied athletes (25).

Perceptions of thermal sensation at the end of exercise were similar for both Pre and Dur with ratings of “warm” compared with the Con trial where ratings of “hot” were reported. The latter values are similar to those reported for able-bodied subjects during arm crank ergometry in hotter conditions (39°C) (27), further illustrating the reduced thermoregulatory capacity in tetraplegic individuals. Wearing the ice vest during exercise in the heat also delayed the increase in perceptions of thermal strain by 2 min compared with Pre cooling. The similar values between trials after this point are most likely due to the ice vest losing its effectiveness as the ice strips thawed, a factor commented on by the majority of subjects. It is likely that both the reduced thermal and cardiovascular strain contributed to the reduced perception of effort during the cooling trials.

Limitations. Although the two subjects with incomplete lesions did demonstrate the greatest $\dot{V}_{\text{O}_2}\text{peak}$ (1.18 and 1.20 l/min), this was not the same for peak power output where, unlike submaximal responses, little relationship between completeness of lesion and peak power output was evident. For these two subjects, however, differences in $\dot{V}_{\text{O}_2}\text{peak}$ were essentially negligible compared with the rest of the group and would not have resulted in different metabolic rates (i.e., heat production) during the 35% $\dot{V}_{\text{O}_2}\text{peak}$ exercise component between sprints. Consequently, because the exercise was a sprint-based protocol, it is unlikely that completeness of lesion would affect heat production per se. However, the incomplete subjects were two of only three subjects to demonstrate any sweating responses during the resting exposure. Although this cannot be discounted in assessing the thermoregulatory data, no obvious link appears to exist within our data between completeness of lesion and thermal parameters. Although previous authors have
observed sweating in this population, it has been either limited (11) or ineffective (22) and is unlikely to have affected the thermal parameters in our population. Furthermore, all core temperature responses for these subjects were within 1 SD of the mean response; inclusion of their data, therefore, did not alter the results of the statistical analysis.

A further point to comment on is the use of the telemetry pill technique. This mode is useful for monitoring transient changes in core temperature of tetraplegic athletes, without causing any discomfort that may be associated with esophageal thermometry. Although Himilos et al. (14) concluded that the telemetry pill was faster to respond to changes in body temperature than rectal temperature, this technique is not without limitations, such as difficulty in determining the exact location of the telemetry pill within the gastrointestinal tract. However, the methods employed within the present investigation should have delimited this potential error by following previous methodological recommendations ensuring reliable data up to 12 h postingestion (20, 29) and being concerned primarily with the cumulative heat gain during each trial.

In conclusion, both cooling strategies facilitated reduced thermal and cardiovascular strain that may translate into improved functional capacity and reduced perceptual responses of trained tetraplegic individuals. Interestingly, the high-intensity nature of the intermittent sprint protocol may have elicited a greater contribution to heat gain from metabolism than previous continuous exercise investigations. Consequently, the particular cooling strategy employed may depend on the specific exercise scenario to be undertaken and whether peripheral or central cooling is the greater requirement.

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REFERENCES