Foot Cooling Reduces Exercise-Induced Hyperthermia in Men with Spinal Cord Injury

TODD A. HAGOBIAN, KEVIN A. JACOBS, B. JENNY KIRATLI, and ANNE L. FRIEDLANDER

Clinical Studies Unit, Veterans Affairs Palo Alto Health Care System, Palo Alto, CA

ABSTRACT

HAGOBIAN, T. A., K. A. JACOBS, B. J. KIRATLI, and A. L. FRIEDLANDER. Foot Cooling Reduces Exercise-Induced Hyperthermia in Men with Spinal Cord Injury. *Med. Sci. Sports Exerc.*, Vol. 36, No. 3, pp. 411–417, 2004. The number of individuals with spinal cord injury (SCI) participating in sports at recreational and elite levels is on the rise. However, loss of autonomic nervous system function below the lesion can compromise thermoregulatory capacity and increase the risk of heat stress relative to able-bodied (AB) individuals. **Purpose:** To test the hypotheses that exercise in a heated environment would increase tympanic temperature (T_{TY}) more in individuals with SCI than AB individuals, and that foot cooling using a new device would attenuate the rise in T_{TY} during exercise in both groups. **Methods:** Six subjects with SCI (lesions C5–T5) and six AB controls were tested in a heated environment (means ± SEM, temperature = 31.8 ± 0.2°C, humidity = 26 ± 1%) for 45 min at 66% ± 5 of arm cranking $\dot{V}O_{2peak}$ and 30 min of recovery on two separate occasions with foot cooling (FC) or no foot cooling (NC) in randomized order. **Results:** During exercise and recovery in both trials, SCI T_{TY} was elevated above baseline ($P < 0.001$) but more so in the NC versus FC trial (1.6 ± 0.2°C vs 1.0 ± 0.2°C, respectively, $P < 0.005$). Within the AB group, T_{TY} was elevated above baseline for both trials ($P < 0.001$) with peak increases of 0.5 ± 0.2°C and 0.3 ± 0.2°C for NC and FC, respectively. T_{TY}, face, and back temperature were higher in both SCI trials compared with AB trials ($P < 0.05$). Heart rate during exercise and recovery was lower in the SCI FC versus SCI NC ($P < 0.05$). **Conclusion:** These results suggest that extraction of heat through the foot may provide an effective way to manipulate tympanic temperature in individuals with SCI, especially during exercise in the heat. **Key Words:** CORE TEMPERATURE, THERMOREGULATION, SKIN TEMPERATURE, RAPID THERMAL EXCHANGE, RTX

Individuals with spinal cord injury (SCI) gain similar fitness and health benefits from exercise as able-bodied (AB) individuals (6), and their level of participation in recreational and elite sports is on the rise. However, individuals with SCI have a compromised ability to thermoregulate, which can lead to increased risk of heat exhaustion, thermal injury, and reduced exercise capacity relative to AB individuals (2). Individuals with SCI have limited autonomic nervous system control below the level of injury, resulting in reduced sweat capacity (22) and limited control of blood flow distal to the lesion (28). The impaired thermoregulatory response is complicated further with high levels of the injury (>T6), which can result in a loss of supraspinal control of the sympathetic nervous system (SNS), reduced overall SNS activity and decreased whole-body catecholamine release (24,25,27). In addition to directly affecting exercise capacity through compromised cardiac output (30) and reduced vascular control (18), suppressed SNS activity can further impair thermoregulatory capacity by reducing catecholamine induced sweat rates in regions above the site of injury. Increased core and skin temperatures in individuals with SCI relative to able-bodied controls have been observed frequently (19,20,28), and risk of hyperthermia increases when ambient temperatures are elevated (11).

Because of the problems with thermoregulation in individuals with SCI, cooling before or during exercise may be beneficial in this population. Whole-body cooling in AB individuals before exercise has been shown to reduce core temperature (3,4), improve endurance performance (4), and decrease muscle temperature (5). However, the reduction in core temperature before exercise tends to be temporary, and benefits usually dissipate within the first 25 min of exercise (3,4). Logistically, site-specific cooling during exercise has more potential, but the results from studies using head/neck cooling (1,12) and ice-packed vests (1,9) are mixed. For example, Armstrong et al. (1) showed no benefit of site specific-cooling (head vs ice-packed vest) on individuals with SCI during exercise, whereas Desruelle and Candas (9) showed that head cooling causes a reduction in heat strain in AB individuals.

Recently, a new cooling device [Rapid Thermal Exchange (RTX), AVAcore Inc., Palo Alto, CA] has been developed that focuses on the arteriovenous anastomoses (AVA) contained beneath the heat exchanging surfaces of the hands and feet. When dilated, AVA promote heat loss by supplying blood to the venous plexus just below the skin surface, conducting heat to the ambient environment, and then returning cooled blood to the core (13). The cooling

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Address for correspondence: Anne L. Friedlander, GRECC, 182B, MB2B, VA Palo Alto Health Care System, 3801 Miranda Avenue, Palo Alto, CA 94304; E-mail: friedlan@stanford.edu.

device uses negative pressure (suction) to increase blood flow to the target AVA and applies an appropriate heat sink to the surface of the skin to increase the extraction of heat from the circulating blood. Previous studies suggest that manipulation of the AVA of the hands and feet using cold water baths or cooled socks can be an effective means of heat removal during rest (16), active exercise (16), and exercise recovery (14,15) in able-bodied subjects exposed to thermally stressful conditions. To our knowledge, use of the AVA to manipulate core temperature in individuals with SCI has not yet been investigated. Extraction of heat through the feet could be especially beneficial to individuals with SCI because it would not inhibit movement of the upper body during exercise. Therefore, the primary purpose of this investigation was to test the temperature regulatory efficacy of the RTX cooling device in SCI and AB individuals during upper-body exercise in the heat. The secondary purpose was to determine the importance of the negative pressure when using the device in individuals with SCI. We hypothesized that 1) arm-cranking exercise in a heated environment would increase tympanic temperature more in SCI than AB subjects, 2) foot cooling using the RTX device would attenuate the rise in tympanic temperature during exercise in both groups, and 3) the device would be more effective when cooling was used in combination with negative pressure in individuals with SCI.

METHODS

Subjects. Seven individuals with SCI and six AB individuals were recruited from within the Veterans Affairs Palo Alto Health Care System (VAPAHCS) by flyers and letters to previous study participants, and from the San Jose Community Center quad rugby league. All subjects were males between the ages of 30 and 60 yr, nonsmoking, and were disease free, as determined by health history questionnaire and medical evaluation. The SCI subjects had spinal cord lesions of long-standing origin (>5 yr) between the range of C5–T5. One subject with SCI was excluded from the study because he experienced an autonomic dysreflexic reaction during both of the trials. Therefore, data from six SCI and six AB subjects are presented in the final analyses. Five of the individuals with SCI were taking prescription antispasmodic medication, and two were taking cholesterol-lowering medication. These prescription drugs are common in individuals with SCI and should not have affected their thermoregulatory capacity. The AB subjects were recruited to match the SCI subjects as closely as possible on age, body weight, body fat percentage, and peak oxygen consumption; however, we were only partially successful as body weight and absolute peak oxygen consumption were different between the two groups (Table 1). Previous studies (10,19,20) have also had difficulties matching SCI and AB subjects on peak oxygen consumption and body weight. In this investigation, we chose to recruit individuals with SCI with a high level of injury to assure a subject pool with thermoregulatory constraints. In general, the higher the site of the lesion, the greater the reduction in capacity for heat dissipation and the greater the impairment in exercise capacity. Despite complicating the matching process, we believed that individuals with SCI with lesions above the level of T6 would benefit the most from use of the foot-cooling device. Written informed consent was obtained from all subjects, and the Stanford University Administrative Panel on Human Subjects in Medical Research approved the study.

TABLE 1. Physical characteristics of SCI and AB subjects.

Variable	SCI	AB
Age (yr)	43.0 ± 3.7	49.8 ± 3.2
Height (cm)	181.7 ± 2.5[a]	184.1 ± 2.8
Weight (kg)	74.5 ± 2.8	91.2 ± 2.6*
Body fat (%)		
Whole body	22.1 ± 3.0	17.8 ± 2.1
Upper body	20.3 ± 3.1	17.1 ± 2.4
Armcrank $\dot{V}O_{2peak}$		
($mL \cdot kg^{-1} \cdot min^{-1}$)	14.4 ± 2.9	18.5 ± 0.6
($L \cdot min^{-1}$)	1.1 ± 0.2	1.7 ± 0.1*
Level of injury	C5–T5	NA

Values are means ± SEM for SCI ($N = 6$) and AB ($N = 6$) subjects.

* Significantly different from SCI ($P < 0.05$).

[a] Self-reported.

SCI, spinal cord injury; AB, able-bodied; $\dot{V}O_{2peak}$, peak oxygen uptake; NA, not applicable.

Screening tests. Upon admission to the Clinical Studies Unit (CSU) at the VAPAHCS, a resting electrocardiogram and medical evaluation were performed on all subjects. After medical clearance, body composition was evaluated by dual-energy x-ray absorptiometry (Hologic QDR 1000W, Bedford, MA) and analyzed by a trained technician. Subjects then performed a continuous progressive exercise test to volitional exhaustion on an arm-cranking device (Monark Inc. 881, Varberg, Sweden). An initial workload of 0 W was increased 5–10 W every 1–2 min. Expired air was analyzed using an online system (Parvomedics TrueMax 2400, Consentius Technologies, Sandy, UT), and peak oxygen consumption ($\dot{V}O_{2peak}$) was determined to be the highest 30-s value obtained during the test. In addition, heart rate (HR) was recorded every minute (Polar Electro Inc. A1, Woodbury, NY) and rate of perceived exertion every other minute (Borg scale).

Testing protocol. Subjects completed two exercise trials in a heated environment (mean ± SEM, temperature = 31.8 ± 0.2°C, relative humidity = 26 ± 1%) on an upper-body arm-cranking device with either foot cooling (FC) or no foot cooling (NC). After an overnight fast, subjects arrived at the CSU fully hydrated having consumed at least 240 mL of water in the previous 2 h and were fed a standardized breakfast (392 kcal, 42% carbohydrate, 40% fat, 18% protein). Subjects were escorted into the heated environment 30 min after completion of the meal. One hour after completion of the meal, the trial began with 10 min of resting data. During the FC trial, cooling was activated after the initial 5 min, allowing for baseline noncooled values for each trial. After 10 min of resting data collection, subjects arm-cranked for 45 min at 66% ± 5 of arm-cranking $\dot{V}O_{2peak}$ followed by 30 min of inactive recovery. Subjects were required to drink 150 mL of water every 15 min throughout exercise and recovery. Tympanic, face, and back temperature were recorded every second with a data logger

(Omega Inc. OM-3000, Stamford, CT), then converted to 5-min averages. Oxygen consumption ($\dot{V}O_2$) was measured during the initial 10 min of rest and 10 min of exercise, and then every 15 min throughout the duration of the trial. $\dot{V}O_2$ values were averaged from the last 3 min of each 5-min sampling period. A Laser Doppler monitor (Moor Instruments Inc., United Kingdom) recorded toe skin blood flow flux (BF_T) in arbitrary perfusion units (V) every second and was averaged for rest, exercise, and recovery. A laser Doppler monitor is a good marker of blood flow that is not influenced by skeletal muscle (23). The BF_T probes were taped on the big toe of both feet during the FC and NC trials with neither socks nor any other type of clothing covering the feet. No fan was used and there was zero wind speed during every trial. In addition to the FC and NC trials, the SCI subjects completed a third trial that consisted of foot cooling with no negative pressure (NP) to test the efficacy of the device with and without negative pressure. Dietary intake was controlled, and exercise was prohibited 24 h before all trials. The order of the tests was randomized with a minimum of 2 d apart between trials.

Foot-cooling device. The RTX cooling device (AVAcore, Inc.) focuses on the heat-exchanging arteriovenous anastomoses in the feet to directly manipulate core body temperature. Local heat exchange is enhanced by the simultaneous application of negative pressure and a cold sink to the vascular structures underlying the sole of the foot. The negative pressure maximizes the blood volume of the distended vascular structures. The device consists of a metallic heat-exchanging surface on which the sole of the foot rests surrounded by a plastic chamber. A neoprene seal above the ankle is connected to the plastic chamber, allowing a vacuum seal. Excess air is then pumped from the device creating a negative pressure while tubing circulates water around the heat-exchanging surface, thus drawing heat back to a small reservoir of cooled water. Cooled blood then returns from the lower extremity, potentially attenuating the rise in core temperature during exercise. The circulating water temperature was 22°C during the cooled trials. When the device was in use, we alternated 4 min of negative (−15 in H_2O) and 1 min of neutral pressure. Alternating pressure facilitated blood return from the lower extremity and minimized blood pooling, which was a primary concern in the SCI subjects. Future versions of the device will have the capacity to calculate heat transfer via the foot by recording inflow/outflow temperatures and flow rates.

Tympanic, face, and back temperature. Tympanic (T_{TY}), face (T_F), and back (T_B) temperature was analyzed with Mon-a-therm temperature probes (Mallinckrodt Medical Inc., St. Louis, MO). T_{TY} was measured in the left ear, T_F on the left cheekbone, and T_B on the upper cervical spine. Each probe was secured to the skin using breathable porous tape (Transpore surgical tape, 3M Healthcare, St. Paul, MN). No fan was used to assure close agreement between T_{TY} and core temperature (7).

Statistical analysis. Data were analyzed using Statistica Inc. software (Tulsa, OK), with values presented as means ± SEM. Because baseline values could have been different for each subject between trials due to small differences in temperature probe and laser Doppler placement, temperature and blood flow responses were calculated as change from baseline. Despite presenting data and graphs as change from baseline, initial resting values for temperature and BF_T responses were not statistically different. To facilitate interpretation of the data, baseline temperature values are also included in the results. A one-factor ANOVA was used to determine between group differences, and a mixed model three-way ANOVA with one between factor (group) and two within factors (cooling and time) was used to determine the group by time interaction. When appropriate, *post hoc* tests of significance were performed with a Tukey HSD test. The level of significance was set at $\alpha < 0.05$.

RESULTS

Tympanic temperature (T_{TY}). Within the SCI group, T_{TY} initial baseline values were 36.3 ± 0.2°C and 36.0 ± 0.2°C for the SCI FC and SCI NC, respectively. T_{TY} in SCI was elevated above baseline for both trials from 20 min of exercise throughout recovery, but the NC T_{TY} was higher compared with the FC T_{TY} from 15 min of exercise throughout recovery (Fig. 1). The maximum rise in T_{TY} was 60% greater in the NC trial with increases of 1.0 ± 0.2°C and 1.6 ± 0.2°C for SCI FC and SCI NC, respectively. Within the AB group, baseline values were 36.5 ± 0.1°C and 36.3 ± 0.1°C for the FC and NC, respectively. T_{TY} in AB was elevated above baseline for both trials from 30 to 45 min of exercise but returned to baseline levels during recovery (Fig. 1). Peak increases in AB did not differ between trials (0.3 ± 0.2°C and 0.5 ± 0.2°C for AB FC and AB NC, respectively). Between the SCI and AB groups, T_{TY} was higher in

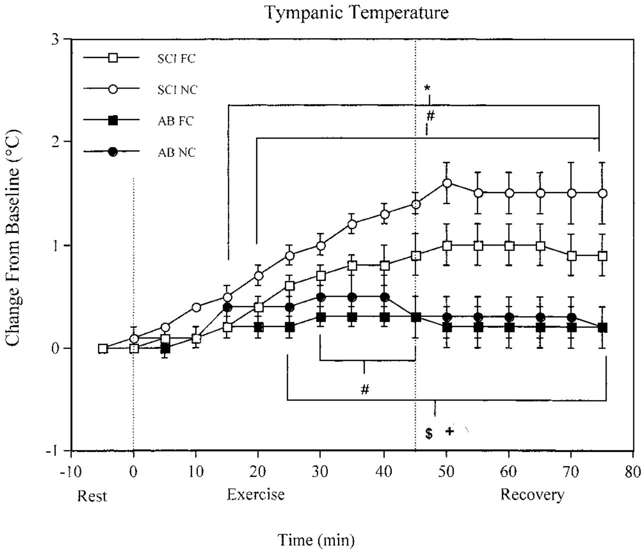

FIGURE 1—Tympanic temperature calculated as change from baseline in degrees Celsius. Values are means ± SEM for SCI ($N = 6$) and AB ($N = 6$). *SCI FC significantly different from SCI NC ($P < 0.0005$); #significantly different from baseline ($P < 0.001$); $AB FC significantly different from SCI FC ($P < 0.05$); +AB NC significantly different from SCI NC ($P < 0.05$). SCI, spinal cord injury; AB, able-bodied; FC, foot cooled; NC, noncooled.

SCI versus AB cooled trial and SCI versus AB noncooled trial from 25 min of exercise throughout recovery.

Face temperature (T_F). Within the SCI group, T_F was significantly elevated above baseline with peak increases of 1.3 ± 0.4°C and 1.7 ± 0.5°C for the SCI FC and SCI NC trials, respectively (Fig. 2). Initial baseline values were 35.6 ± 0.2°C and 35.4 ± 0.2°C for the SCI FC and SCI NC, respectively. T_F tended to be higher from 15 min of exercise throughout recovery in the SCI NC versus SCI FC but was not significant. Within the AB group, T_F was significantly reduced below baseline, with peak reductions of −1.3 ± 0.8°C and −1.5 ± 0.8°C for the AB FC and AB NC trials, respectively. Baseline values were 35.5 ± 0.2°C and 35.5 ± 0.3°C for the AB FC and AB NC, respectively. Between the SCI and AB groups, T_F was higher in the SCI FC versus AB FC and SCI NC versus AB NC from 30 min of exercise throughout recovery.

Back temperature (T_B). Within the SCI group, T_B baseline started at 35.4 ± 0.3°C for FC and 35.2 ± 0.2°C for NC, and was elevated above baseline with peak increases of 0.7 ± 0.4°C and 1.4 ± 0.6°C for the FC and NC trials, respectively (Fig. 3). T_B tended to be higher in the SCI FC versus SCI NC from 5 min of exercise throughout recovery, but there was no significant difference. Within the AB group, T_B was significantly reduced below baseline, with peak reductions of −2.1 ± 0.9°C and −2.2 ± 0.8°C for the AB FC and AB NC trials, respectively. Initial baseline values for T_B were 34.7 ± 0.4°C for both AB trials. Between the SCI and AB groups, T_B was higher in the SCI FC versus AB FC and SCI NC versus AB NC from 30 min of exercise throughout recovery.

Cardiovascular and physiological responses. Oxygen consumption during exercise was significantly elevated compared with rest and recovery in both SCI and AB trials (Table 2). The AB subjects tended to have a higher submaximal $\dot{V}O_2$ response compared with SCI subjects during exercise for both trials due to the higher workloads in the AB subjects. HR during exercise and recovery was significantly lower in SCI FC compared with SCI NC, and HR during exercise was significantly higher in AB compared with SCI during the FC trial (Table 2). Respiratory exchange ratio (RER) tended to be lower in the SCI FC versus SCI NC (0.96 vs 1.0, respectively), but was not significantly different between trials (Table 2). There were no differences in RER between the SCI and AB trials. During exercise, BF_T was significantly elevated compared with rest in the FC and NC trials for both the SCI and AB subjects, and tended to be higher in the NC versus FC trial for SCI only (Table 3).

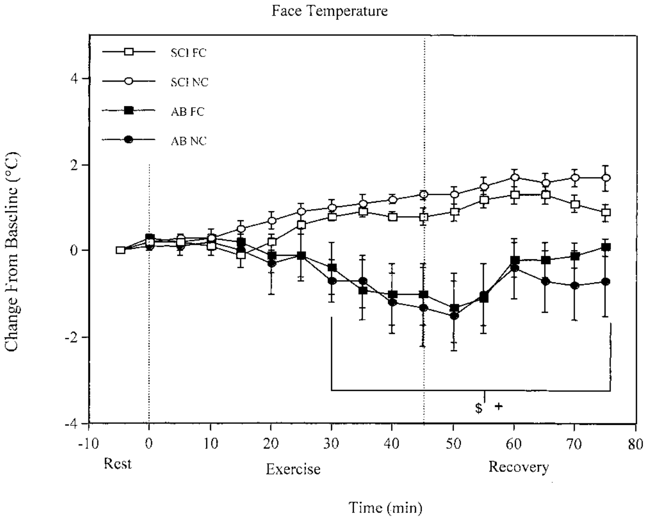

FIGURE 2—Face temperature calculated as change from baseline in degrees Celsius. Values are means ± SEM for SCI (N = 6) and AB (N = 6). $AB FC significantly different from SCI FC ($P < 0.05$); +AB NC significantly different from SCI NC ($P < 0.01$). SCI, spinal cord injury; AB, able-bodied; FC, foot cooled; NC, noncooled.

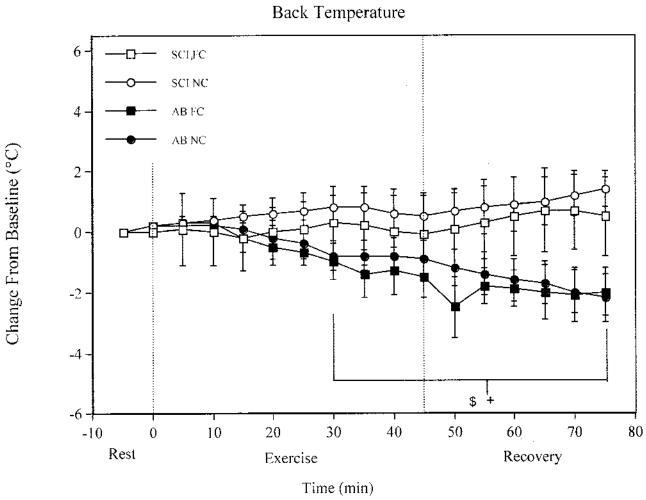

FIGURE 3—Back temperature calculated as change from baseline in degrees Celsius. Values are means ± SEM for SCI (N = 6) and AB (N = 6). $AB FC significantly different from SCI FC ($P < 0.05$); +AB NC significantly different from SCI NC ($P < 0.05$). SCI, spinal cord injury; AB, able-bodied; FC, foot cooled; NC, noncooled.

TABLE 2. Cardiovascular and physiological responses for SCI and AB subjects during rest, exercise, and recovery.

Variable		Rest	Exercise	Recovery
$\dot{V}O_2$ (mL·kg^{-1}·min^{-1})				
SCI	FC	3.9 ± 0.2	9.0 ± 1.1#	4.0 ± 0.3
	NC	3.6 ± 0.2	9.0 ± 1.1#	4.2 ± 0.3
AB	FC	4.1 ± 0.1	12.2 ± 1.0#	4.3 ± 0.2
	NC	4.2 ± 0.1	12.6 ± 0.9#	4.5 ± 0.2
HR (beats·min^{-1})				
SCI	FC	76 ± 4	97 ± 6*+	81 ± 4*
	NC	73 ± 4	106 ± 10+	88 ± 6+
AB	FC	76 ± 5	109 ± 6+$	86 ± 7+
	NC	76 ± 5	110 ± 6+	86 ± 7+
RER				
SCI	FC	0.96 ± 0.03	0.96 ± 0.02	0.86 ± 0.03+
	NC	0.97 ± 0.03	1.00 ± 0.05	0.88 ± 0.02+
AB	FC	0.93 ± 0.02	0.99 ± 0.03	0.88 ± 0.03+
	NC	0.91 ± 0.02	0.97 ± 0.02	0.85 ± 0.03+
Workload (W)				
SCI		0	20 ± 7△	0
AB		0	36 ± 6	0

Values are means ± SEM for SCI (N = 6) and AB (N = 6).
* SCI FC significantly different from SCI NC ($P < 0.05$).
$ AB FC significantly different from SCI FC ($P < 0.05$).
\# Significantly different from rest and recovery ($P < 0.05$), + Significantly different from rest ($P < 0.05$).
△ SCI workload significantly different than AB workload ($P < 0.05$).
SCI, spinal cord injury; AB, able-bodied; FC, foot cooled; NC, noncooled; $\dot{V}O_2$, O_2 uptake; HR, heart rate; RER, respiratory exchange ratio.

TABLE 3. Toe skin blood flow calculated as change from baseline during foot cooled and noncooled trial for SCI and AB subjects during rest, exercise, and recovery.

Variable	Rest	Exercise	Recovery
FC trial BF_T (V)			
SCI cooled foot	0.03 ± 0.03	0.36 ± 0.25+	0.25 ± 0.24
AB cooled foot	−0.02 ± 0.03	0.34 ± 0.25+	0.23 ± 0.18
NC trial BF_T (V)			
SCI	0.09 ± 0.12	0.62 ± 0.27+	0.33 ± 0.19
AB	0.02 ± 0.05	0.23 ± 0.18+	0.15 ± 0.14
NP trial BF_T (V)[a]			
SCI cooled foot	0.03 ± 0.04	0.19 ± 0.16	0.14 ± 0.16
AB	NA	NA	NA

Values are means ± SEM for SCI ($N = 6$) and AB ($N = 6$).
+ Significantly different from rest ($P < 0.05$).
SCI, spinal cord injury; AB, able-bodied; FC, foot cooled; NC, noncooled; NP, no pressure; BF_T, toe skin blood flow.
[a] NP for SCI only; NA, not applicable.

SCI NP trial. T_{TY} was elevated above baseline in the SCI NP trial from 20 min of exercise throughout recovery and was higher in the SCI NP from 40 min of exercise throughout recovery compared with SCI FC (Fig. 4). BF_T did not increase significantly between rest and exercise in the NP trial as it did in the SCI foot-cooled trial (Table 3). The lack of cooling effect on T_{TY} in the NP trial may have resulted from a reduction of blood flow to the cooled foot in the absence of negative pressure.

DISCUSSION

The primary finding of this investigation was that the RTX foot-cooling device attenuated the rise in tympanic temperature in individuals with SCI during exercise in the heat. Because individuals with SCI have a compromised thermoregulatory system and have been shown to be at a greater risk of thermal stress, they may gain substantial benefit from such a device. In contrast, AB individuals did not show much benefit from the foot-cooling device, mainly because AB subjects showed little change in T_{TY} in either trial. This is likely due to the ability of AB individuals to dissipate the heat generated during the upper-body arm-cranking exercise independent of foot cooling.

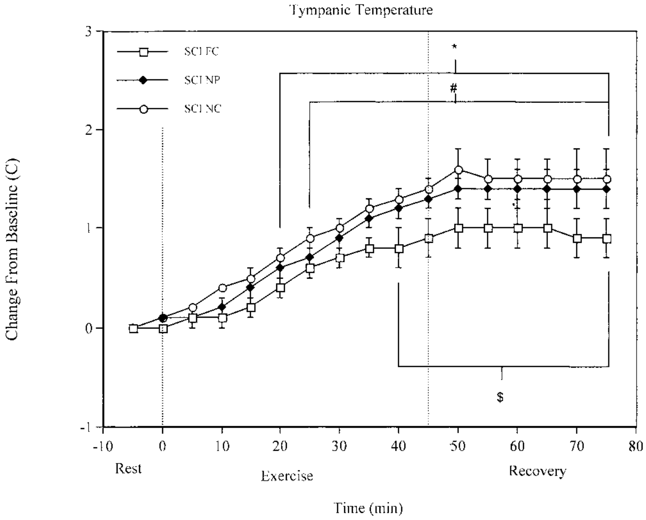

FIGURE 4—Tympanic temperature for all three SCI trials calculated as change from baseline in degrees Celsius. Values are means ± SEM for SCI ($N = 6$). *SCI FC significantly different from SCI NC ($P < 0.0005$); [#]significantly different from baseline ($P < 0.0001$); [$]SCI FC significantly different from SCI NP ($P < 0.0001$). SCI, spinal cord injury; FC, foot cooled; NP, no pressure; NC, noncooled.

Temperature and cardiovascular responses. Individuals with high (>T6) and complete spinal lesions have less sympathetic nervous system control (see Introduction) and are more susceptible to hyperthermia during exercise compared with SCI individuals with low spinal lesions and/or AB controls (21,27). In this investigation, the ambient temperature of 31.8°C and exercise at 66% of $\dot{V}O_{2peak}$ for 45 min placed a thermal stress on the SCI individuals as shown by a peak increase in T_{TY} of 1°C and 1.6°C for the FC and NC trials, respectively. This increase in core temperature during exercise in the heat is consistent with previous research using similar subjects (8,21). However, foot cooling both attenuated the rise in T_{TY} and reduced mean exercise HR in individuals with SCI (Fig. 1 and Table 2). Because the workload and $\dot{V}O_2$ were similar in the SCI trials, HR was likely elevated during the NC trial to compensate for a reduced stroke volume resulting from decreased central blood volume (dehydration and/or increased peripheral flow) in order to maintain cardiac output. Previous research has observed a decreased HR with either whole-body precooling or site-specific cooling during exercise in AB individuals (4). However, to our knowledge, no research has shown a decreased HR or T_{TY} with any method of cooling during exercise in SCI individuals.

Whole-body cooling before exercise in AB individuals has produced favorable results by reducing core temperature (3–5), lowering muscle temperature (5), and increasing performance (4). However, whole-body precooling may be difficult for individuals with SCI to administer. On the other hand, site-specific cooling is more accessible, does not hinder range of motion during exercise, and potentially could have the same benefits as precooling. To our knowledge, only one study has evaluated site-specific cooling (head vs ice-packed vest) in SCI subjects during exercise in the heat (1). Armstrong et al. (1) showed no differences in heat storage, skin temperature, or core temperature between cooled and noncooled trials in individuals with SCI, suggesting that the local cooling devices were either not powerful enough or poorly targeted. Therefore, it appears that by targeting the AVA in the current investigation, foot cooling provided greater benefits to individuals with SCI than head or vest cooling. AVA blood in the feet is increased during exercise and up to 30% of total cardiac output might pass through the venous plexus during exercise (13). A potential problem with the head wrap and ice-packed vest is that the skin contact temperature of the devices may fluctuate; thus, heat transfer can be impaired. For example, the contact temperature could be too warm, which would reduce the conduction gradient or too cold causing local vasoconstriction and preventing effective heat exchange. In the current investigation, the heat-exchanging surface of the cooling device was kept at 22°C, and alternating pressure kept blood flowing to and from the cooled foot (Table 3). In addition, as the authors in the Armstrong paper suggest, the efficiency of head and vest cooling is reduced by the tendency of the apparatus to absorb heat from the surrounding environment. A potential confound when comparing the efficacy of the cooling methods in the Armstrong study with the current foot-cooling methodology is that despite working at higher workloads, subjects in the Armstrong et al. study showed smaller increases in core temperature during the control test than our subjects in the NC trials (1.0 vs 1.6°C, respectively). This was likely due to the fact that Armstrong et al. used highly fit, heat acclimatized wheelchair athletes with predominantly low-level paraplegia (one of six subjects had an injury above T6) who exercised only for 30 min. Subjects in our study were relatively unfit, had high lesions (C5–T5), and exercised for 45 min. At 30 min, the rise in tympanic temperature in our noncooled trial was similar to that observed by Armstrong et al. (1) in the control test (approximately 1°C). As suggested by our AB subjects or previously (15), higher core temperatures and larger temperature differentials can increase the efficacy of a cooling methodology.

The increased T_{TY} during exercise and recovery in the SCI trials compared with the AB trials is consistent with some previous studies (10,29) but not others (19,20). A few explanations exist for the difference in T_{TY} between AB and SCI individuals. First, because upper-body exercise uses smaller muscle groups than lower-body exercise, the AB subjects may not have been using sufficient muscle mass to stress their thermoregulatory system sufficiently given they are used to whole-body exercise. Second, AB individuals have a greater ability to employ evaporative cooling than individuals with SCI because they have an intact autonomic nervous system and are able to activate sweat glands directly through innervation and through an increase in circulating catecholamine levels. This is also reflected in the higher T_F and T_B in the SCI group for both trials compared with the AB group (Fig. 2, Fig. 3) and has been found previously (10,20,28). Finally, because the AB individuals were approximately 17 kg heavier than the SCI individuals, they have more tissue to heat before a measurable change in T_{TY} would be seen. In contrast, the higher absolute workload performed by the AB subjects would be expected to increase the quantity of heat generated, thus counteracting some of the benefits of the increased body mass on heat storage capacity.

Toe skin blood flow (BF_T) was measured in this investigation to determine the local hemodynamic response to cooling with and without negative pressure. Comparison of flux values obtained in the NP and FC trials during exercise suggests that negative pressure may improve flow when using the device (Table 3). Although measured blood flow differences were small, the inability of the device to prevent the rise in T_{TY} in the NP trial further supports the hypothesis that alternating pressure is an important component of foot cooling in SCI individuals. The largest increase in BF_T during exercise was observed in the SCI NC trial. Such a finding was expected as the reduction in vasomotor control and inability of individuals with SCI to redirect blood flow to working muscles has been well documented (24,27,28). Our results agree with previous research in which high- and low-level SCI subjects demonstrated greater increases in leg skin blood flow compared with AB subjects during moderate intensity arm-cranking exercise (28). However, others have not documented similar increases in flow (29).

Methodological consideration. We were partially successful in matching the SCI and AB groups. To control for the quantity of heat generated, we tried to match the SCI and AB subjects as closely as possible on arm-crank $\dot{V}O_{2peak}$, body fat percentage, body weight, and age. To date, no study has matched SCI and AB individuals on absolute $\dot{V}O_2$ and relative intensity during exercise. By matching the groups on peak capacity, the intent was to keep the relative and absolute workloads identical during testing to assure that the metabolic flux rates and heat generated would be equivalent. Even though the upper- and lower-body fat percentage, relative $\dot{V}O_{2peak}$ ($mL \cdot kg^{-1} \cdot min^{-1}$), and steady-state $\dot{V}O_2$ response during exercise were not significantly different between groups, AB subjects were capable of working at higher workloads. However, if the subjects with SCI in this investigation had been exercising at the same absolute $\dot{V}O_2$ as the AB subjects, additional heat would have been generated in the SCI subjects, which would probably have further increased T_{TY} in the SCI subjects. Therefore, closer matching of the subjects would have amplified, not negated, the observed differences in T_{TY}, T_F, and T_B between SCI and AB trials. Matching on upper- and lower-body fat percentage and body weight is important because the thermoregulatory response and heat storage generated during exercise may be different if a larger subcutaneous fat content and/or a greater ratio of body surface to body mass exists possibly affecting core temperature by altering the body's ability to dissipate heat.

In this investigation, we used T_{TY} as a surrogate for core temperature, as core temperature measured in a specific body region may vary compared with another region (e.g., T_{TY}, rectal, and esophageal). However, studies have shown that T_{TY} temperature has a high correlation with rectal temperature in SCI and AB individuals (7,26), and T_{TY} temperature provides an accurate assessment of changes in body temperature (17). In this investigation, T_{TY} was measured in the left ear of every subject, and no fan or direct airflow was allowed in either trial. Under these controlled conditions, a change in T_{TY} should be an adequate estimate for a change in core temperature.

CONCLUSION

The major finding of this investigation was that extraction of heat through the foot attenuated the rise in tympanic temperature in SCI individuals during exercise and inactive recovery in the heat. Tympanic temperature was also significantly elevated in SCI compared with the AB subjects in both the cooled and noncooled trials. The negative pressure component of the cooling device appears to be important in individuals with SCI, as cooling without negative pressure did not reduce the rise in tympanic temperature during exercise. The results suggest that site-specific RTX cooling may provide an effective way to manipulate core temperature in individuals with SCI that have high levels of injury (>T6) and compromised thermoregulatory capacity, especially during exercise in the heat.

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Results of the present study do not constitute endorsement of the RTX foot-cooling device by the authors or ACSM.

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