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Experimental study on the effectiveness of the PCM cooling vest in persons with paraplegia of varying levels

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ABSTRACT

Persons with paraplegia (PA) from thoracic spinal cord injury (T1-T12) are prone to thermal stress during exercise due to impaired thermoregulation. This study evaluates the effectiveness of phase change material (PCM) cooling vests on persons with PA of different levels of injury during exercise in hot exposure. Sixteen participants were recruited and divided to three groups based on injury level; high-thoracic T1-T3, mid-thoracic T4-T8, and low thoracic T9-T12 to perform a 30-min arm-crank exercise at a 30 °C room condition. Two types of PCM vests at melting temperature of 20 °C were tested: i) V1 with PCM covering the trunk of 3.4 kg overall vest mass and ii) V2 with PCM covering chest and upper back of 2.17 kg overall vest mass. High thoracic and low-thoracic groups performed NV and V1 tests; whereas, mid-thoracic group performed NV, V1, and V2 tests. Heart rate, core, and skin temperatures were monitored during 15-min preconditioning, 30-min exercise, and 15-min recovery. In addition, thermal comfort, sensation, skin wettedness, and perceived exertion were recorded during exercise only.

The main findings were that the effectiveness of the cooling vest was dependent on injury level and portion of sensate skin of trunk covered by the PCM packets. Rise in core temperature (ΔT_{cr}) was reduced significantly for the low-thoracic group during exercise and recovery (ΔT_{cr} = 0.41°C, 0.26°C for NV and V1; respectively, $p<0.05$). For the mid-thoracic group, both V1 (p = 0.001) and V2 (p = 0.008) were effective in reducing ΔT_{cr} compared to the NV test at the end of the recovery period (0.74°C, 0.42°C, 0.56°C, for NV, V1 and V2; respectively). For the high-thoracic group, V1 was not effective in reducing core temperature ($p>0.05$). For the mid-thoracic group, V2 at 36% lower mass significantly improved thermal comfort (p = 0.0004) compared to the NV test and was as effective compared to V1 in reducing core temperature.

1. Introduction

The body temperature of able-bodied people, defined as weighted sum of core temperature (T_{cr}) and skin temperature (T_{sk}), is maintained stable at 36.8 ± 0.2 °C through active thermoregulatory responses at the skin (vasomotor, sudomotor and shivering) (Little and Little, 1989; Widmaier et al., 2008). However, persons with spinal cord injury (SCI) at the thoracic vertebrae (T1-T12), named persons with paraplegia (PA), lose the ability to regulate T_{cr} when exercising or under heat exposure (Dongmei et al., 2012). This is attributed to the decentralization of the sympathetic spinal cord from the hypothalamus, which causes loss of blood vessels' dilation or contraction (vasomotor effect), as well as, sweating glands' stimulation (sudomotor response) (Garstang and Miller-Smith, 2007). Moreover, after thoracic SCI, the arterial blood vessels undergo alterations in their structure (diameter and wall thickness) leading to overall reduction in the cardiac output (Attia and Engel, 1983; Petrofsky, 1992; West et al., 2012; Wilsmore 2007; Mneimneh et al., 2019b). Reduction in cardiac output results in reduction of skin blood flow which limits the heat transfer through blood circulation between the core and the skin. These alterations in thermal physiology of persons with PA lead to to thermal stress episodes during prolonged exercise in in moderate and warm ambient conditions as a result of the stored heat in the body. Accordingly, their thermoregulatory responses at sensate skin portions of body alone are unable to restore T_{cr} to its thermal neutral state (Petrofsky, 1992; Choi and Loftness, 2012).

The seriousness of the health risk in persons with PA when exercising in warm conditions varies as per the severity of their injury and its level. Persons with PA's injury is in general distinctive by the paralysis of legs (thighs, calves, and feet) with the loss of physical sensation in the legs

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Nomenclature

AIS	ASIA impairment scale
ASIA	American Spinal Injury Association
HR	heart rate
ISNCSCI	International Standards for Neurological Classification of Spinal Cord Injury
NV	no vest case
PA	paraplegia
PE	perceived exertion
PCM	phase change material
RH	relative humidity
RPM	rotation per minute
SCI	spinal cord injury
T_{body}	body temperature
T_{cr}	core temperature
T_{sk}	skin temperature
V1	vest-type1 with phase change material covering all trunk
V2	vest-type2 with phase change material covering all upper trunk
ΔT_{body}	change of body temperature
ΔT_{cr}	change of core temperature
ΔT_{sk}	change of skin temperature
$\Delta T_{sk,mean}$	change of mean skin temperature

and trunk (Kirshblum et al., 2011). However, the portion of impairment in the trunk is not the same among thoracic spinal cord injuries as shown in Fig. 1(a–c). People with (T1-T2-T3) SCI have impairment in the whole trunk area except upper part of chest and shoulders and 75% of trunk skin area is insensate (see Fig. 1(a). People with (T4-T8) SCI have impairment from the level of the lower side of the chest (level of the nipples) and upper back until end of trunk and 50% of trunk skin area is insensate (see Fig. 1(b). Finally, people with (T9-T12) SCI have impairment in the portion of the middle back and the abdomen until end of trunk and only 25% of trunk skin area is insensate (see Fig. 1(c) (Salloum et al., 2007; Kirshblum et al., 2011).

Since the core temperature of the trunk is considered vital for maintaining regular body temperature, heat and exercise prove challenging to persons with PA to preserve their body thermal homeostasis. The trunk is perceived to dominate both: (i) skin wetness perception as it contains 48% of body sweating glands and (ii) coldness sensitivity as it occupies 49% of body thermoreceptors at the skin, among body segments (Dykes et al., 2002; Douzi et al., 2019). Therefore, when a significant portion of the trunk skin area becomes insensate, heat loss at the periphery may not be enough to balance the heat gain induced by a high metabolic rate.

Not only is the degree of impairments in thermoregulatory responses different among thoracic SCI levels, but also metabolic rate obtained during exercise differed among them. Previous studies reported that the same external load of exercise performed by persons with PA produced different values of oxygen uptake, an indication of different metabolic rates (Veeger et al., 1991; Wicks et al., 1983). These studies showed that people with an injury level above T6 (T1-T5) had a significantly lower oxygen uptake (22 ± 6%) compared to those of injuries below T6 (T6-T10) ($p<0.05$). Therefore, cardiorespiratory responses in persons with PA may vary based on injury level and affect amount of heat gained in the body during exercise.

To prevent unsafe elevations of T_{cr} in persons with PA, experimental studies have tested various cooling methods for this vulnerable population. Among these methods is wearing phase change material (PCM) vests (Griggs et al., 2014; Armstrong et al., 1995; Trbovich et al., 2014). The reported performance of PCM vests varied depending on the timing of use (before, during, or after exercise) and the duration of its application. Trbovich et al. (2014) assessed the effect of PCM cooling vests of melting temperature ($15^{\circ}C$) on a group of people with cervical and thoracic SCI who played a 60-min sport game in a wheelchair at moderate room conditions. Results showed that the cooling vest had an insignificant effect on reducing the rise in T_{cr} during the exercise

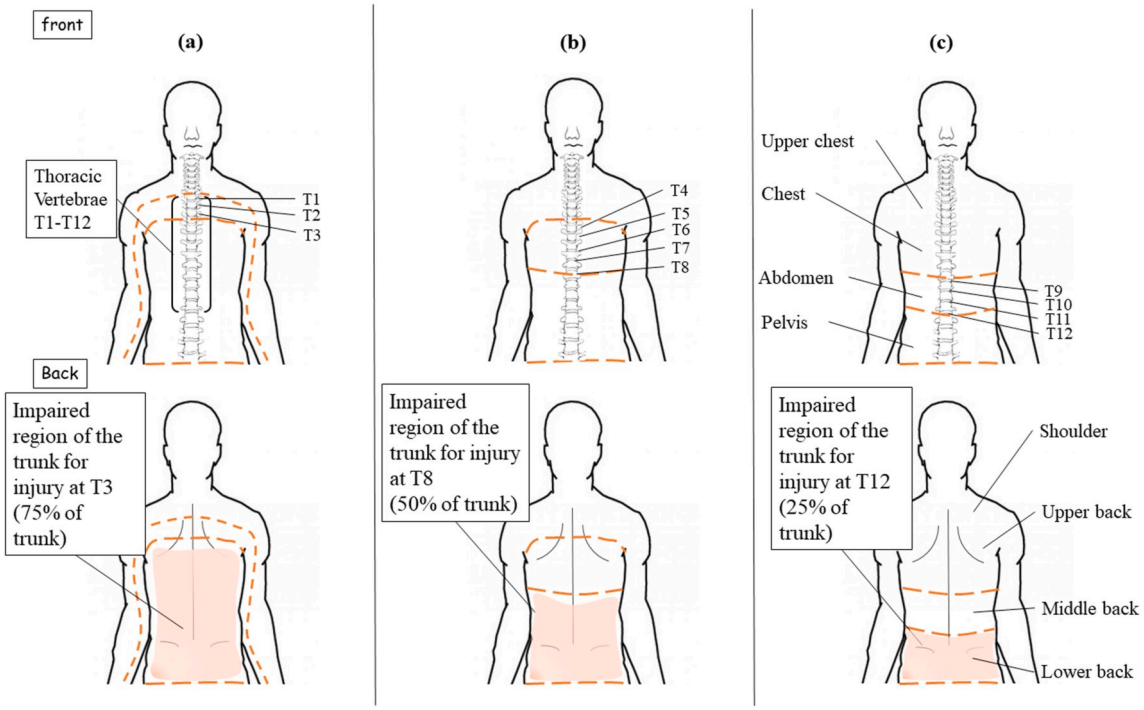

Fig. 1. Schematic showing the frontal and back regions of impairment in the trunk due to SCI at the thoracic vertebrae (a) T1-T3 (b) T4-T8 (c) T9-T12; (Kirshblum et al., 2011).

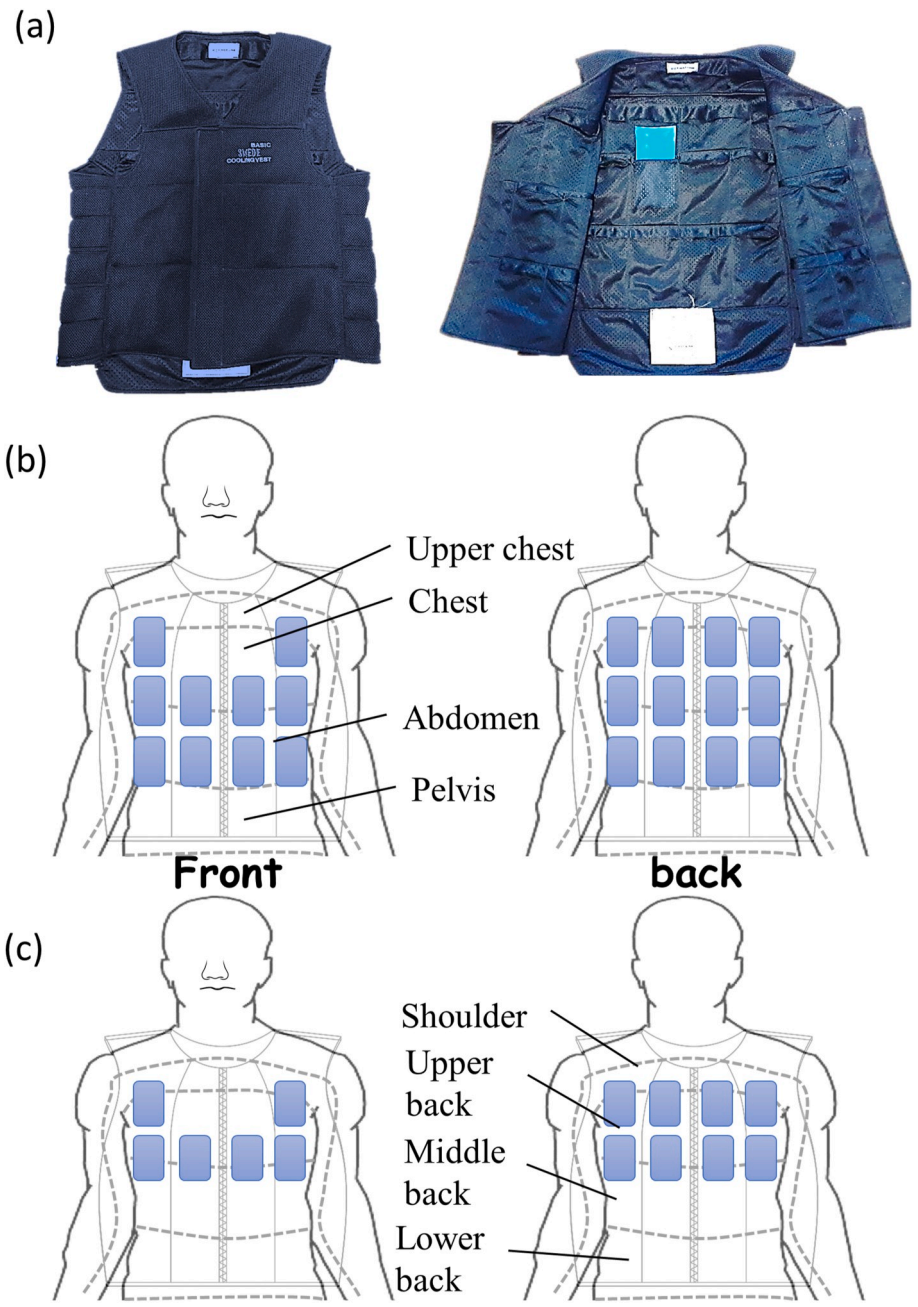

Fig. 2. Picture of (a) PCM cooling vest and blue PCM packet inserted (b) configuration of type1 covering chest, upper back, middle back and abdomen, and (c) configuration of type2 covering chest and upper back. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

($p>0.05$). Likewise, Armstrong et al. (1995) assessed the effect of an ice-cooling vest on wheelchair athletes during a hot-exposure exercise where only four out of six subjects were persons with PA. Insignificant difference in T_{cr} at the end of the exercise was determined between the cases with and without the vest ($p>0.05$). Although cooling vests, whether using ice or PCM, did not result in significant reduction of T_{cr} compared to the cases without a cooling vest, the experimental literature findings were not conclusive. These studies had not considered the dependency of thermal physiological changes on the thoracic injury level in the body of persons with PA. Thus, the ineffectiveness of the cooling vest could be attributed to the reduced portion of the sensate skin area depending on the level of injury resulting in reduced heat losses at the insensate skin and causing core temperature to increase.

With very few published studies about the effectiveness of PCM cooling vest for persons with PA during exercise, the question remains inconclusive as to whether the cooling vest is a good strategy that can be adapted to the thermal physiology in persons with PA. The effectiveness of a cooling vest is influenced by the significant role of the trunk in maintaining stable T_{cr}. To propose a design for an effective cooling vest for persons PA, it is important to understand the extent of thermoregulation dysfunction in persons with PA and the impact of these disruptions on the performance of the PCM vest in cooling the trunk active areas. Mneimneh et al. (2018, 2019a) developed a bioheat model for persons with PA of (T6-T12) SCI to predict their thermal response and validated it with published experimental studies. The PA-bio heat model was integrated with the PCM cooling vest model of Itani et al. (2016). When cooling the whole trunk skin area at same melting point, Mneimneh et al. (2018, 2019a) reported an increase in sensible heat

Table 1
Physical properties of the two configurations of the cooling vest.

Parameter	*V1*	*V2*	% $\left(\frac{V2-V1}{V1}\right)$
Total PCM mass (kg)	3.41	2.17	- 36%
Total PCM coverage (cm^2)	2240.5	1425.8	- 36%
% coverage from total area (6666 cm^2) of trunk	34%	21%	–
Total PCM coverage at the **front** of trunk (cm^2)	1018.4	611.1	- 40%
Total PCM coverage at the **back** of trunk (cm^2)	1222.1	814.7	- 33%
% coverage at the **front** of trunk (3333cm^2)	31%	18%	
% coverage at the **back** of trunk (3333cm^2)	37%	24%	–

losses at the sensate skin of the trunk (active trunk segments for T6-T12) which were higher than heat losses at the impaired skin of the trunk (impaired trunk segments for T6-T12). This proved that cooling the insensate skin area of the trunk was not effective in reducing core temperature in persons with PA during exercise and hot ambient conditions. Hence, it would be appropriate to propose a PCM cooling vest in which the PCM packets are placed at the sensate skin of the trunk, thus reducing the overall weight of the cooling vest and providing the same efficacy. To the authors' knowledge, previous studies did not address the PCM cooling vest design adaptive to the physiology of persons with PA of varying injury levels.

Therefore, the aim of this study is to investigate experimentally the effectiveness of the PCM cooling vest for persons with PA during exercise and the extent of its performance on the thoracic injury level. The vest effectiveness is evaluated by performing human subject experiments at warm room conditions (30 °C, 50%) during arm-crank exercise. The participants are divided into three groups based on anatomy and physiology of thoracic injury (T1-T12). Two types of PCM cooling vest are tested. With the first type, PCM packets covered trunk skin area (chest, abdomen, upper back, middle back) and was tested in the three groups. With the second, the PCM packets covered only the sensate skin of trunk based on injury level and was tested in one group only. The two cases are compared to the case of no vest test. Accordingly, the hypothesis is that (i) the effectiveness of PCM cooling vest is significantly dependent on injury level and (ii) cooling the sensate skin of the trunk rather than the whole trunk may be effective in attenuating the rise in T_{cr} for persons with PA.

2. Subjects and methods

The current study focuses on improving the design of PCM cooling vest of melting temperature ($20°C$) to be adaptive to the thoracic injury level. The vest was used during exercise and hot exposure; for the sake of reducing the unsafe increase in core temperature. This target was achieved by conducting human subject experiments in a controlled environment. Participants with PA performed experiments inside a climatic chamber of warm conditions (30 °C, 50%) where all performed exercise using an arm-crank ergometer at specific load (30 W) during different types of tests.

2.1. Categorization of human subjects

During recruitment of persons with PA, the lesion level was obtained from participants' medical records and radiological findings. In addition, the severity of injury was determined based on a physical exam performed by the neurosurgeon in charge for recruitment, following the International Standards for Neurological Classification of Spinal Cord Injury (ISNCSCI) exam (Kirshblum et al., 2011). According to the anatomy and physiology of thoracic spinal cord, the participants were divided into three groups: Group (I): high-thoracic (T1-T3); **Group (II)**: mid-thoracic (T4-T8); and **Group (III):** low-thoracic (T9-T12) as shown in Fig. 1(a–c) (Kirshblum et al., 2011). This categorization intended to compare thermoregulation during exercise with and without the vest on people with thoracic SCI based on their metabolic rate, portions of sensate skin area of the trunk, as well as, thermoregulatory disruptions (Kehn and Kroll, 2009; Melo et al., 2018).

2.2. Cooling vest arrangements tested on human subjects

A polyester cooling vest that was commercially designed to hold up to 22 equally sized PCM packets was used in this study. The PCM packets used in the experiment were made of a salt mixture of sodium sulfate and water known as Glauber's salt (Gao et al., 2012) with a melting point of $20°C$. The thickness, area, mass, and heat of fusion of one PCM packet were 1.3 cm, 101.84 cm^2, 155 g, and 113.0 kJ/kg respectively (Swedish Emergency and Disaster Equipment AB, 2017; All Safe Industries, 2017). The melting period duration of the selected PCM packets could extend up to 2 h under hot conditions ($35°C$) and moderate metabolic rates ($\cong 3\ METs$) as reported in previous studies in literature (Itani et al., 2016, 2017).

The current study focuses on two types of PCM vests where each type covered a certain area of the trunk; however, it is worth noting that the covered trunk area might have different portions of sensate and insensate areas depending on the injury level. The first vest named, vest-type1 (V1), comprised of PCM packets, which covered the chest, upper back, middle back, and abdomen as seen in Fig. 2(a). All three groups were tested with this type of vest. In the second type of vest, named vest-type2 (V2), PCM packets were placed on the chest and upper back to target sensate skin area only (see Fig. 2(b)), which resulted in lower vest weight. This type of vest was tested for **Group (II)** as this group had variation in the sensate/insensate portion of the trunk unlike **Groups (I)** and **(III)**.

The comparison between two types of vest is indicative whether cooling the sensate skin using V2 rather than whole trunk using V1 can be as effective in reducing T_{cr} for the mid-thoracic group. The mass of cooling vest and the PCM coverage area at the trunk were both 36% less in V2 than in V1. Table 1 summarizes the physical properties of the two types of the cooling vest and the percentage difference between them. Based on the categorization of the recruited participants, **Groups (I)** and **(III)** performed two experiments: no-vest (NV) and V1 tests; whereas, **Group (II)** performed three experiments: NV, V1, and V2 tests.

2.3. Sample size

A minimum sample size per group was a requirement to detect the significant change in T_{cr} (ΔT_{cr}) and T_{sk} (ΔT_{sk}) to assess the effect of cooling vest on persons with PA. Thus, a priority power analysis calculated the minimum number of participants per group using GPower software of version 3.1.9.4. The sample size analysis was based on a power of test of 90% and a level of significance α of 5% (Griggs et al., 2014; Price and Campbell, 2003; Webborn et al., 2010). Sixteen participants with PA joined this experimental work. For **Group (I)**, a sample size of three participants (n = 3) was assigned for a minimum significance of $\Delta T_{cr} = 0.6 \pm 0.2°C$ and $\Delta T_{sk} = 1 \pm 0.2°C$. For **Group (II)**, a sample size of eight participants ($n = 8$) was defined for a minimum significance of $\Delta T_{cr} = 0.25 \pm 0.2°C$ and $\Delta T_{sk} = 1 \pm 0.2°C$. This number of participants was recruited to increase statistical power about effectiveness of the two configurations of the cooling vest for the mid-thoracic group. Finally, a sample size of five participants ($n = 5$) was assigned for **Group (III)** for a minimum $\Delta T_{cr} = 0.3 \pm 0.2°C$ and $\Delta T_{sk} = 1 \pm 0.2°C$.

2.4. Subjects (recruitment and medical examination)

Ethical approval to carry the study on persons with PA was obtained from the Institutional Review Board (IRB) at the American University of Beirut (AUB). Sixteen persons with SCI who are wheelchair dependent

Table 2
Physical properties of participants.

Subject	Age (yrs.)	Gender	Weight (kg)	Height (cm)	Level of Injury	Duration of Injury (yrs.)	ASIA Impairment Scale (AIS)	Group
1	30	M	80	175	T3	2	B	I
2	33	M	71	178	T3	8	B	I
3	24	M	65	165	T3	2	B	I
Mean (SD)	**29 ± 5**	-	**72 ± 8**	**173 ± 7**	-	**4 ± 3**		
4	30	F	48	160	T8	12	B	II
5	42	F	62	162	T8	24	C	II
6	32	M	70	175	T8	11	B	II
7	25	M	77	180	T8	7	C	II
8	40	M	60	165	T6	33	C	II
9	22	M	55	170	T8	1	C	II
10	36	M	70	175	T7	6	B	II
11	25	M	70	172	T6	4	C	II
Mean (SD)	**32 ± 7**	-	**64 ± 10**	**170 ± 7**	-	**12 ± 11**		
12	30	F	60	165	T11	14	C	III
13	36	F	45	160	T12	10	B	III
14	31	M	80	175	T11	7	C	III
15	25	M	69	171	T12	6	B	III
16	35	M	82	183	T12	1.5	B	III
Mean (SD)	**31 ± 4**	-	**67 ± 15**	**171 ± 9**	-	**8 ± 5**		

B = sensory incomplete; C = motor incomplete (AIS)

Table 3
Reference scales for subjective ratings.

Thermal Comfort Scale (Gagge et al., 1967)	0 *neutral*	1 *comfortable*	2 *slightly uncomfortable*	3 *uncomfortable*	4 *very uncomfortable*	5 *extremely uncomfortable*
Wetness of Skin and Clothing Scale (Grigg 2016)	1 *more dry than normal*	2 *normal dryness*	3 *slightly wet*	4 *wet*	5 *body wet*	6 *body wet, clothing sticks to the skin*
Head, neck and shoulders Thermal Sensation Scale (Toner et al., 1986)	0 *neutral*	1 *slightly warm*	2 *warm*	3 *hot*	4 *very hot*	5 *extremely hot*
Trunk Thermal Sensation Scale (Toner et al., 1986)						
Perceived Exertion Scale (Borg, 1982)	0 *extremely light*	1 *very light*	2 *fairly light*	3 *somewhat hard*	4 *hard*	5 *very hard*

Table 4
Average load and RPM for three groups within three tests.

	NV			V1			V2			mean±SD
Parameter	Group I	Group II	Group III	Group I	Group II	Group III	Group I	Group II	Group III	
Avg. load (W)	30.3 ± 4	30.9 ± 4	30.0 ± 9	31.3 ± 5	30.4 ± 5	30.3 ± 5	–	31.8 ± 5	–	30.7 ± 0.6
Avg. RPM	67.7 ± 20	61.4 ± 18	62.4 ± 19	69.3 ± 21	61.5 ± 19	62.0 ± 16	–	68.4 ± 20	–	63.1 ± 4

were selectively recruited for this study. The inclusion criteria were specified and approved by IRB as follows: (i) complete/incomplete thoracic SCI (T1-T12); (ii) the age in the range of 25–45 yrs; (iii) the average weight in the range of 75 ± 10 kg and the average height in the range of 170 ± 10 cm; (iv) the duration of injury of minimum one year for medical stability; (v) the participant of a wheelchair user; and (vi) no implanted electro-medical device or gastrointestinal disease. As a result, the recruited participants were middle-aged (31 ± 6 yrs) males and females with incomplete thoracic SCI (T3-T12) with an average weight (67 ± 11 kg) and an average height (171 ± 7 cm). The least injury duration was more than one year (9 ± 9 yrs), and the cause was trauma of the spinal cord due to vehicle and constructions' work accidents.

All participants confirmed their commitment to a physiotherapy program provided by the recreation center and participated in exercise or performed outdoor chores at least two times per week. Table 2 presents participants' physical properties including age, height, body mass, as well as, injury level, its severity and its duration. No significant difference of these physical properties ($p>0.05$) was obtained between groups. Since participants had the injuries older that one year, the medical status and physiological responses were assumed stable as the body would become adaptive to the complications of the injury (Krause and Crewe, 1991). In addition, because of lack of availability of eligible participants with complete thoracic SCI during recruitment, persons with incomplete thoracic SCI of ASIA B or C were accepted for participation. There is low likelihood of intact thermoregulation in these persons as previous studies reported that even when sensory innervation is partially preserved, complete loss of autonomic innervation can occur (e.g., ASIA B or C) (Cariga et al., 2002; Taylor, 2016).

The clothing/uniform of the participants consisted of a 50% cotton-50% polyester t-shirt, trousers, underwear-pants, underwear-shirts, socks, and shoes with an average dry thermal resistance of 0.5 ± 0.1 clo (0.0775 ± 0.01 m^2 K/W). Each participant's first visit was a medical examination, a briefing about experimental protocol, listing physiological and psychological parameters to be recorded, and signing a consent form.

2.5. Physiological and physical measurements

Dry bulb temperature and relative humidity sensor (OM-EL_WIN_USB, OMEGA, UK, 0.5 °C and 0.5% resolution) measured every 1 min

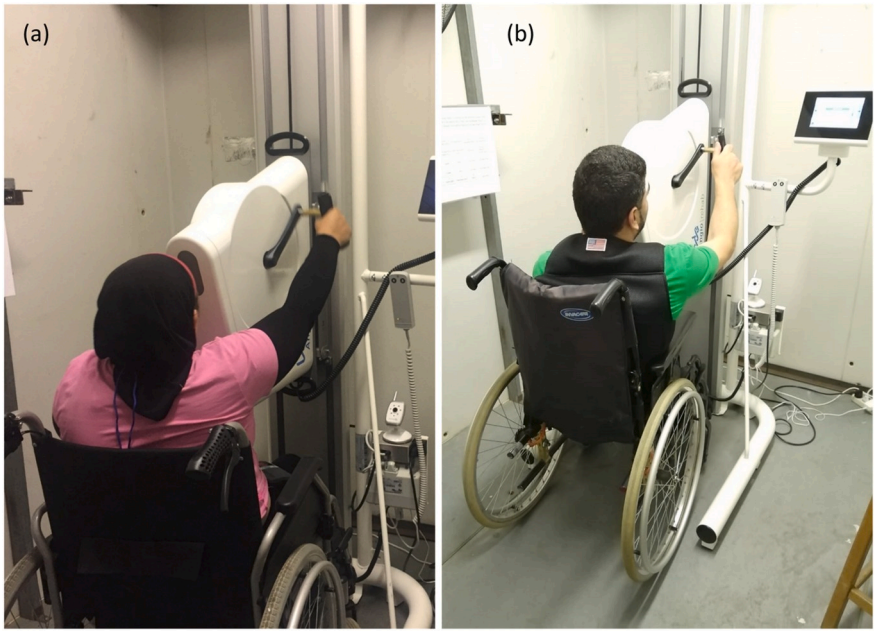

Fig. 3. Pictures showing (a) one female participant doing exercise without vest and (b) one male participant doing exercise with vest.

Location:
Heat Transfer & Energy Research Laboratory, Irani Oxy Building

Prior to the experimental session

- ingest an activated telemetric pill at a minimum of 2-3 hours

Arrival on-site

- Briefing on experiment
- Empty bladder and avoid fluid/food intake
- Preparation of participant (skin sensors allocation, synchronization of pill with monitor, attachment of pulse oximeter sensor to the ear
- Rest for 30 minutes in the research laboratory (24°C , 50%)

Time= 0 mins → **Enter the climatic chamber**
(30.6 ± 0.1°C, 50 ± 5%)

- Participant rests for 15 minutes
- Beginning of tympanic (core) temperature and heart rate recording

Time= 15 mins → **Start of arm-crank exercise**

- Participant exercises on a arm-crank ergometer at a power load of 35 W (at about 2.8 Mets) for a period of 30 minutes

	Group I	Group II	Group II
No-vest	x	x	x
With-vest-type1	x	x	x
With-vest-type2		x	

- Votes are reordered every 10 minutes about thermal comfort, thermal sensation, skin wettedness and perceived exertion

Time= 45 mins → **End of exercise**

- Recovery period of 15 minutes

Time= 60 mins → **Exit the climatic chamber**

Fig. 4. Schematic of a brief description of the experimental procedure.

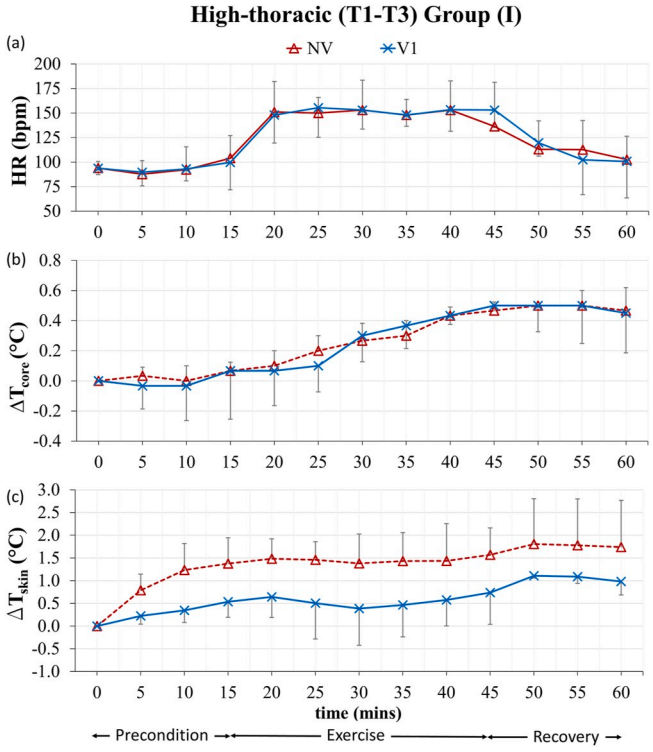

Fig. 5. Plot of (a) heart rate values (b) change in core temperature (ΔT_{cr}), and (c) change in skin temperature (ΔT_{sk}) (mean ± SD) for Group (I).

the ambient conditions of the climatic chamber. The accuracy of this sensor is reported to be $\pm 0.5^{\circ}C$ at typical temperature range (35–80 °C) and 3% at typical relative humidity range (20–80%). Temperature iButton sensors (iButton DS19221, Maxim Integrated, CA, USA, 0.0625 °C resolution) were taped on seven human body segments at 10 positions (chest, upper back, lower back, pelvis, forehead, forearm, palm, thigh, calf and foot) and recorded a measurement every 1 min throughout the 1-h period of preconditioning, exercise, and post exercise. The average accuracy of the iButton temperature sensors is 0.1 °C

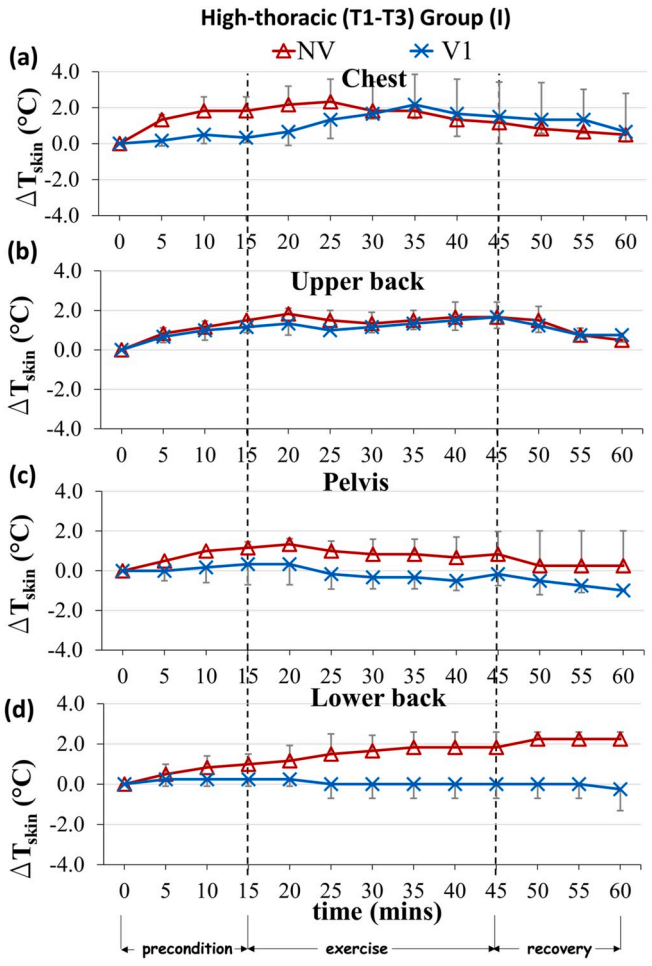

Fig. 6. Plot of change in skin temperature (ΔT_{sk}) (a) chest (b) upper back (c) pelvis (d) lower back for Group (I).

when used at the environmental conditions of ($30°C$ and 50%) with a maximum deviation of 0.4 °C (van Marken Lichtenbelt et al., 2006). In order to ensure proper contact with the skin, a surgical tape was used to place the sensors on the different segments (van Marken Lichtenbelt et al., 2006). Mean skin temperature values were calculated using Hardy et al. (1938) weighting formula of Eq. (1):

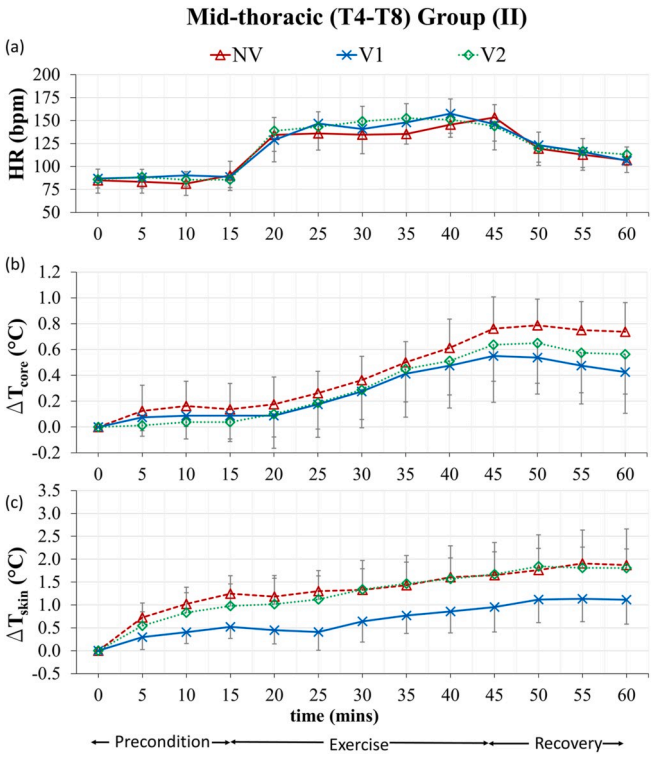

Fig. 8. Plot of (a) heart rate values (b) change in core temperature (ΔT_{cr}) and (c) change in skin temperature (ΔT_{sk}) (mean ± SD) for Group (II).

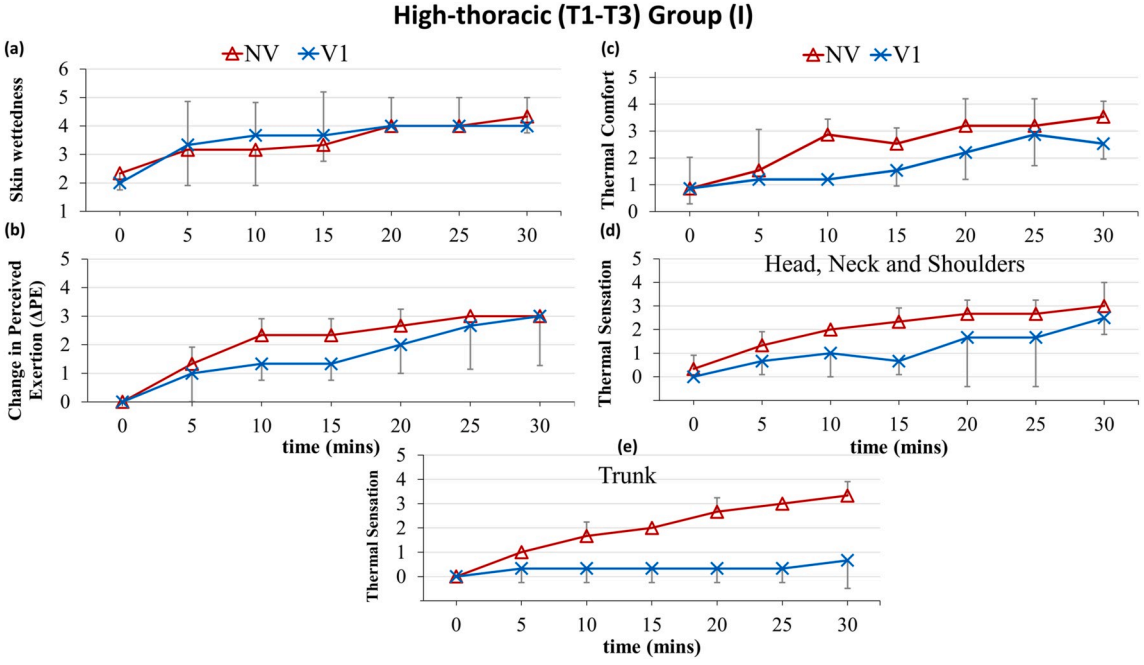

Fig. 7. Plot of (a) skin wettedness (b) ΔPE (change in perceived exertion) (c) thermal comfort (d) thermal sensation at head, neck and shoulders (e) thermal sensation at trunk, for Group (I).

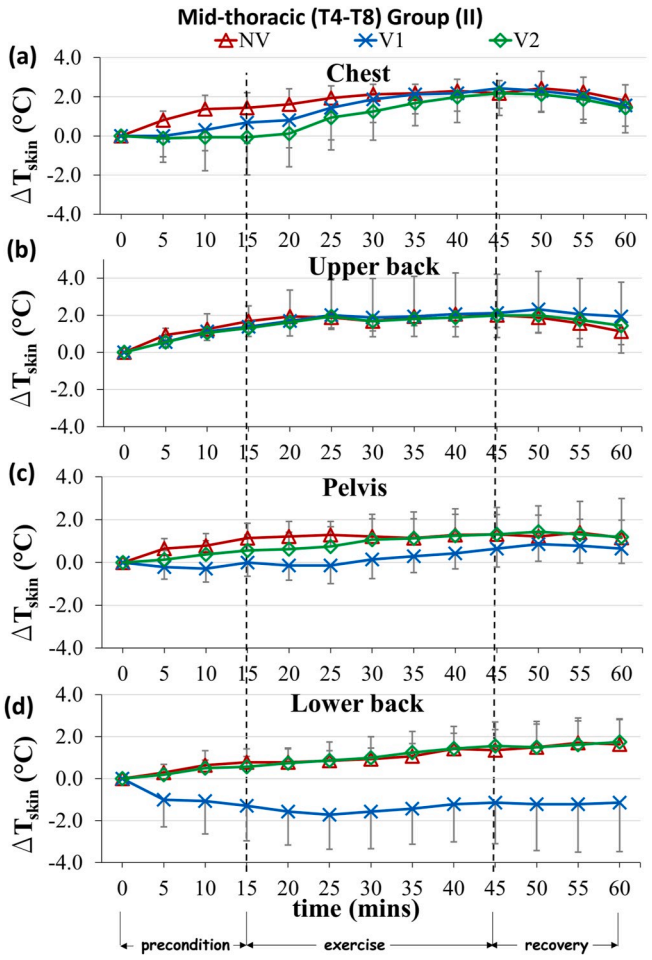

Fig. 9. Plot of change in skin temperature (ΔT_{sk}) (a) chest (b) upper back (c) pelvis (d) lower back for Group (II).

$$T_{sk,mean} = 0.35 \times T_{trunk} + 0.19 \times T_{thigh} + 0.14 \times T_{forearm} + 0.13 \times T_{calf} + 0.07 \times T_{forehead} + 0.05 \times T_{palm} + 0.07 \times T_{foot} \quad (1)$$

where the trunk skin temperature was calculated by averaging the skin temperatures of chest, upper back, lower back, and pelvis.

Heart rate was recorded every 5 min using a pulse oximeter (Model 2500A PalmSAT, NONIN, USA, ±3 bpm accuracy). The values of T_{cr} were measured in two ways: using an activated ingestible pill and using an infrared tympanic thermometer, IRTT. The ingestible pill (eCelsius, BodyCap, France) was configured using e-Celsius Performance Manager software and its monitor (eViewer Perf CE monitor, BodyCap, France) to read every 30 s the gastrointestinal temperature, as an indicator of T_{cr}. The accuracy of the pill is $\pm 0.2^{\circ}C$. In addition, recording of the tympanic temperature was done every 5 min using IRRT (Braun ThermoScan 7 IRT6520, Braun, Kronberg, Germany, accuracy $\pm 0.2^{\circ}C$).

Change in body temperature (ΔT_{body}) was calculated using the formula of Eq. (2a) (Burton, 1935; Griggs et al., 2014; Song et al., 2015):

$$\Delta T_{body} = 0.8 \times \Delta T_{cr} + 0.2 \times \Delta T_{sk,mean} \quad (2a)$$

In addition, the amount of heat stored (H_s) in the body during exercise when not wearing the cooling vest and during was defined as follows (Burton, 1935; Chou et al., 2008):

$$H_s = m_{body} \times C_p \times \frac{\Delta T_{body}}{t} \quad (W) \quad (2b)$$

where m_{body} is the mean body mass of sample (kg), C_p is the body specific heat (3490J/kg·°C), ΔT_{body} is the change in mean body temperature, and t (s) is the exercise duration.

The thermal sensation of head, neck, shoulders, and trunk on a scale of 0 to 5; wetness sensation on skin and clothing on a scale of 1 to 6; overall thermal comfort sensation on a scale of 0 to 5; and the rating of perceived exertion on a scale of 0 to 6 were evaluated from the actual votes of the subjects at the beginning of exercise and every 10 min throughout the test (Gagge et al., 1967; Borg, 1982; Toner et al., 1986; Reinertsen et al., 2008; Itani et al., 2018; Qi et al., 2015; Griggs, 2016). Table 3 summarizes the different reference scales of the subjective voting by the participants. These subjective questionnaires were explained to the participants on their first visit before any scheduled experiment.

2.6. Experimental design

All experiments conducted were at the same time in the afternoon inside a climatic chamber. The latter was equipped by a centralized air-conditioning ducted system and contained the arm-crank ergometer (Angio rehab with automatic stand, Lode, Netherlands). All participants performed the arm-crank exercise at constant load of 30 W to limit the variability in metabolic rate generation between subjects of the same group (Trbovich et al., 2016). Furthermore, previous studies in literature reported similar experiments for persons with SCI at constant load of exercise (Petrofsky, 1992; Yamasaki et al., 2001; Ishii et al., 1995). Summary session report of average load and rotation per minute (RPM) was obtained at the end of each exercise from the screen of the ergometer and results for each group showed no difference between NV, V1, and V2 tests as seen in Table 4. However, performing the same load of exercise, persons with PA are expected to generate different metabolic rates based on injury level because the latter affects maximal oxygen uptake as lung capacity is lower in high thoracic levels (Veeger et al., 1991; Wicks et al., 1983; Brown et al., 2006). Fig. 3(a–b) shows two of the recruited participants: (a) one female not wearing the vest and (b) one male wearing the vest doing the arm-crank exercise inside the climatic chamber.

The climatic chamber conditions were set at warm humid conditions of 30 °C room temperature set point and 50% relative humidity. These conditions were monitored and measured using temperature and a relative humidity sensor. The reported measurements for all experiments showed a small deviation from set conditions ($30.6 \pm 0.1^{\circ}C$ and $50 \pm 5\%$). Fig. 4 summarizes the detailed steps of the protocol on the day of the experiment. During the 1-h experiment, core and skin temperatures were recorded every minute using the ingestible pill and skin sensors respectively, but for monitoring purposes, tympanic temperature and heart rate values were checked every 5 min under the surveillance of a nurse. Precautions were implemented for stopping the experiment if any of the two conditions occurred to avoid any risk for the participants (Griggs et al., 2014): (i) the core temperature reaches 38.5 °C and/or (ii) if the participant wishes to stop any time during the experiment.

3. Data analysis methodology

Comparison of the effectiveness of the cooling vest was considered within each group separately due to the variability of metabolic rate among thoracic SCI levels at the same load of arm-crank exercise (30W). The physiological responses (T_{cr},T_{sk}, HR), as well as, subjective voting (thermal comfort, sensation, skin wettedness and perceived exertion) of the participants were analyzed using the Statistical Package for Social Sciences (SSPS version 25). For groups I and **III**, paired-sample tests (parametric and non-parametric tests), were found suitable since this study aimed to compare the measured parameters before and after using the cooling vest (paired sample: NV vs. V1) at an interval of 5 min for the whole 1-h experiment. If the data was normally distributed, paired

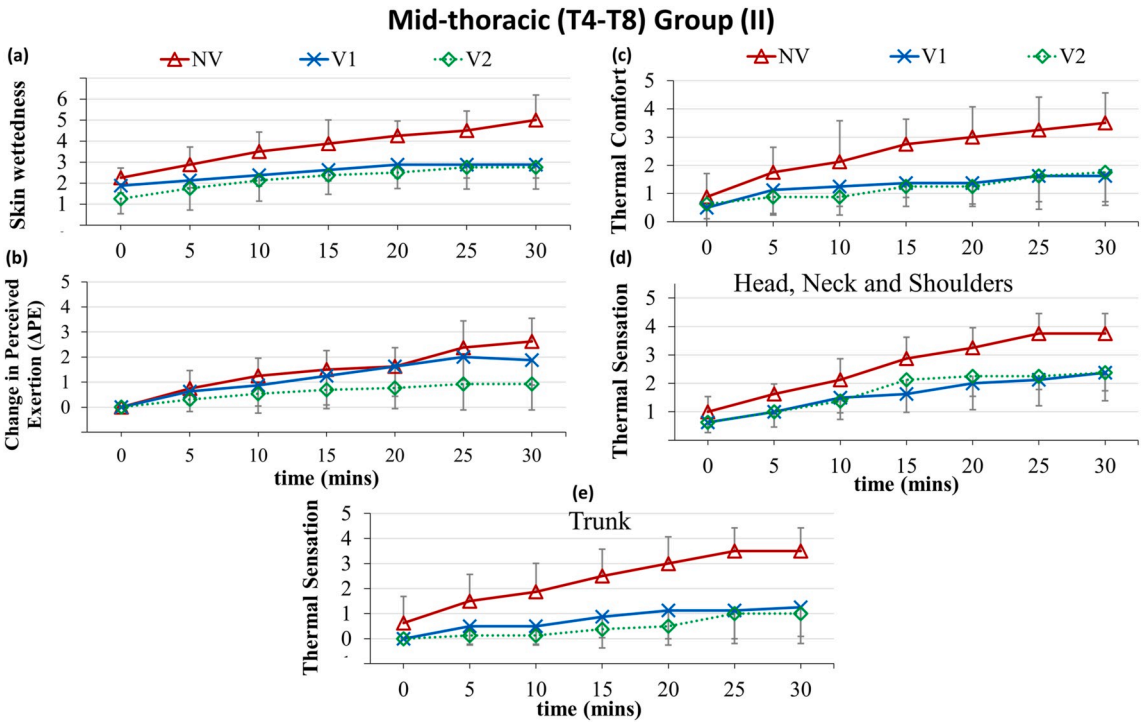

Fig. 10. Plot of (a) skin wettedness (b) ΔPE (change in perceived exertion) (c) thermal comfort (d) thermal sensation at head, neck and shoulders (e) thermal sensation at trunk, for Group (II).

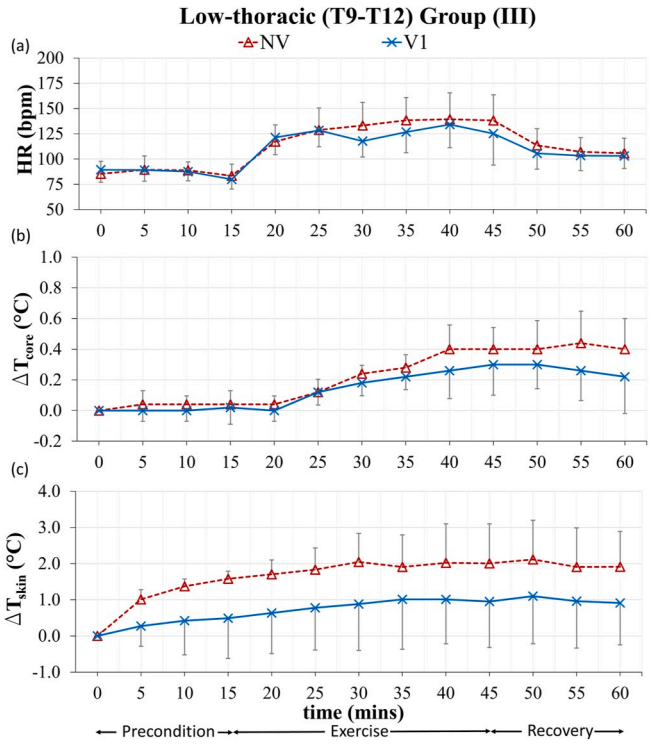

Fig. 11. Plot of (a) heart rate values (b) change in core temperature (ΔT_{cr}) and (c) change in skin temperature (ΔT_{sk}) (mean ± SD) for Group (III).

sample t-Test was used; otherwise, the data was evaluated using the Wilcoxon signed-rank test. The sample size of **Group (I)** (n = 3) was found not to affect the data analysis of this group due to the fact of limited heterogeneity in the sensate skin portion of the torso of the high-thoracic SCI group (Goosey-Tolfrey et al., 2008; Hazra and Gogtay, 2016; Griggs et al., 2014; Price and Campbell, 2003; Armstrong et al., 1995). For **Group II**, two-way ANOVA with repeated measures (test x time) was chosen since the changes in the physiology were investigated under three conditions. Previous studies in literature applied this test (Armstrong at al., 1995; Trbovich et al., 2014; Price and Campbell, 2003). Significance was accepted at the $p < 0.05$ level. Where significance was obtained, Scheffé *post hoc* analysis was undertaken. All data were reported as mean (±SD).

4. Results and discussion

All experiments were carried out until the end of their allocated time. A description of physiological and subjective findings, as well as, its corresponding discussion were established for each group in this section.

4.1. Group I: high-thoracic group (T1-T3)

At the baseline of the experiment, Group (I) showed insignificant difference in the values of *HR*, T_{cr} and $T_{sk,mean}$ between NV and V1 tests (94.0 ± 6.6, 93.7 ± 6.5 bpm; 37.07 ± 0.46, 37.10 ± 0.52 °*C*; 31.25 ± 0.23, 30.54 ± 0.69 °*C*). Fig. 5(a–c) presents values of *HR*, ΔT_{cr} and $\Delta T_{sk,mean}$ during the complete 1-h of the experiment. In Fig. 5(a), *HR* values showed insignificant difference in V1 compared to NV ($p > 0.05$). In Fig. 5(b), there was no significant difference in ΔT_{cr} between NV and V1 during preconditioning, exercise, and recovery period ($p > 0.05$). In Fig. 5(c), $\Delta T_{sk,mean}$ was lower in V1 compared to NV during the complete 1-h experiment (average difference = 0.82 ±0.1°*C*).

No significant difference of T_{sk} values of trunk segments was found at the baseline of the experiment for NV and V1 tests (chest: 32.48 ± 0.27, 32.44 ± 1.53; upper back: 33.13 ± 0.48, 33.44 ± 0.58; pelvis: 33.62 ± 1.54, 32.94 ± 1.61; lower back: 34.76 ± 0.77, 34.94 ± 1.48; $p > 0.05$). Fig. 6(a–d) shows the change in segmental skin temperature (ΔT_{sk}) for the trunk segments (a) chest, (b) upper back, (c) pelvis, and (d) lower back. In all segments of the trunk, ΔT_{sk} was less in V1 compared to the NV test (mean difference of ΔT_{sk} 1.1 ± 0.5°*C*, 1.0 ± 0.2°*C*, 1.0 ± 0.5°*C* for chest, pelvis, and lower back; respectively; $p<0.05$) except for the

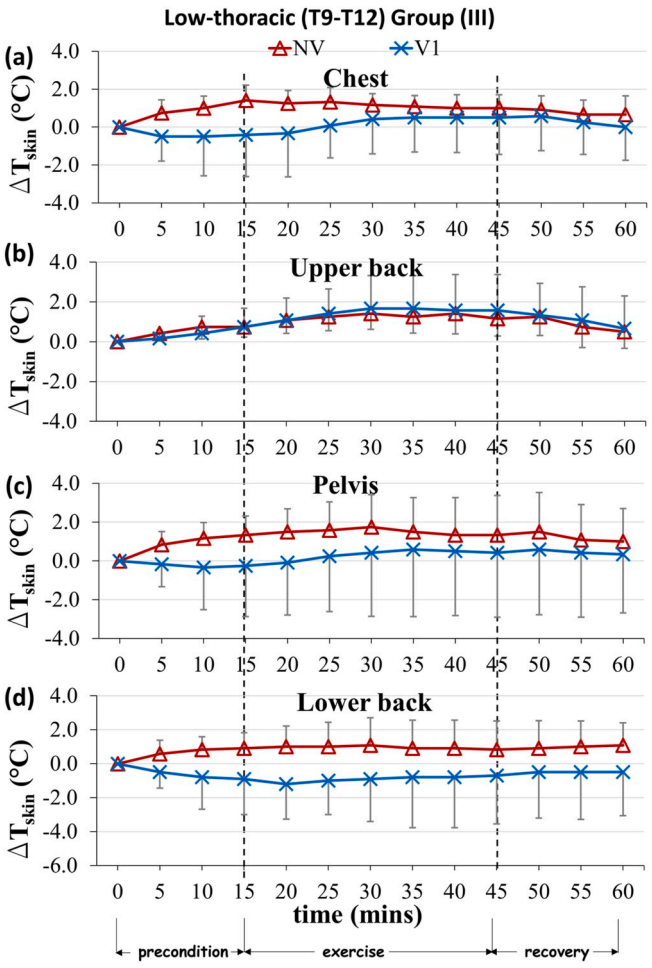

Fig. 12. Plot of change in skin temperature (ΔT_{sk}) (a) chest (b) upper back (c) pelvis (d) lower back for Group (III).

upper back that showed no difference.

Fig. 7(a–e) demonstrates the results of subjective voting of the participants on (a) skin wettedness, (b) perceived exertion, (c) thermal comfort, and (d) thermal sensation at the head, shoulders, and neck, and (e) thermal sensation at the trunk during exercise. It is clear from Fig. 7 (a) that wearing the vest has no effect on skin wettedness. Fig. 7(b) does not show an improvement in the perceived exertion of subjects (mean difference: 1 ± 0.5) which indicates that wearing the vest causes less exhaustion during exercise. Furthermore, Fig. 7(c) shows improvement in thermal comfort from "slightly uncomfortable" to "comfortable" during the first 15 min of the exercise in V1 test compared to NV, but changes to "uncomfortable" until the end of the exercise. Thus, the improved comfort is insignificant during exercise ($p>0.05$). Fig. 7(d–e) shows an insignificant decrease in thermal sensation at head, shoulders, neck, and trunk (mean difference: 0.9 ± 1, 1.6 ± 0.3; $p > 0.05$); respectively.

The physiological findings of **Group (I)** indicated that although $T_{sk,mean}$ values were reduced while using V1, the cooling vest had no effect on reducing T_{cr} values. More precisely, when the sensate skin of the trunk (chest and upper back) cooled, its temperature increased similarly to the NV condition at the end of the experiment. Hence, preserved vasodilation response at sensate skin of the trunk in Group (I) allows cooler blood to circulate from the periphery to the core when using V1. Whereas, insensate skin temperature dropped significantly when covered with V1 compared to NV because of absence of vasodilation response in this area. However, the limited sensate skin area at the trunk (not exceeding 25% from its area) was insufficient to reduce T_{cr} values for Group (I). Furthermore, cooling the insensate skin of trunk had no effect in enhancing body heat dissipation at the periphery. Subjective voting of thermal comfort and sensation during exercise showed insignificant improvement in psychological perception analogous to the insignificant effect on T_{cr} values. Thus, persons with high-thoracic injury should seek out other cooling methods that reduce the rise in T_{cr} values and improve thermal comfort and sensation during exercise in heat (Trbovich, 2019).

4.2. Group II: mid-thoracic (T4-T8)

Initially (time = 0 min), Group (II) had insignificant difference in the values of *HR*, T_{cr} and $T_{sk,mean}$ between NV, V1 and V2 tests (85 ± 12, 86.8 ± 10, 85.8 ± 15 bpm; 36.95 ± 0.23, 37.08 ± 0.33, $36.96 \pm 0.32\,^{\circ}C$; 32.2 ± 1.05, 32.47 ± 0.68, $32.65 \pm 1.1\,^{\circ}C$). Fig. 8(a–c) presents values of *HR*, ΔT_{cr} and $\Delta T_{sk,mean}$ during a complete 1-h exercise. In Fig. 8(a), *HR* values do not show significant difference in V1 and V2 compared to NV ($p > 0.05$). Fig. 8(b) shows ΔT_{cr} for the three tests. From the initial time of preconditioning (t = 0 min) until the end of the exercise (time = 45 min), the average ΔT_{cr} values showed negligible difference between the three tests ($p > 0.05$). However, the deviation started to appear during V1 ($0.26 \pm 0.04^{\circ}C; p = 0.024$) and V2 ($0.20^{\circ}C \pm 0.03^{\circ}C; p = 0.034$) at the end of exercise (time = 45 min) until the end of the recovery period (time = 60 min) both compared to NV. Fig. 8(c) at the end of exercise shows $\Delta T_{sk,mean}$ values were lower in V1 compared to NV and V2 (mean difference $= 0.45 \pm 0.15^{\circ}C; p = 1.03E-11$); whereas, no significant difference was found between V2 and NV ($p > 0.05$).

No significant difference of T_{sk} values of trunk segments was found at the baseline of the experiment for NV, V1, and V2 tests (chest: 33.49 ± 0.8, 33.43 ± 1.0, 33.43 ± 1.0; upper back: 33.16 ± 0.8, 33.79 ± 1.4, 33.75 ± 1.3; pelvis: 32.72 ± 1.5, 32.52 ± 1.3, 32.92 ± 1.7; lower back: 33.85 ± 1.6, 32.40 ± 2.1, 34.22 ± 1.1; $p > 0.05$). Fig. 9(a–d) shows the values of ΔT_{sk} for the trunk segments (a) chest, (b) upper back, (c) pelvis, and (d) lower back. In Fig. 9(a), chest shows lower change during preconditioning and first 15-min of exercise (time = 30 min) at mean difference $0.7^{\circ}C$ and $0.85^{\circ}C$ for V1 and V2 compared to NV, respectively. This difference was minimized after this period to become statistically insignificant ($p > 0.05$) during recovery. Fig. 9(b) shows that the upper back did not have significant change between three tests ($p > 0.05$). Whereas, as seen in Fig. 9(c–d), the pelvis and lower back showed significant decrease during V1 compared to NV and V2 ($p = 0.001$).

Fig. 10(a–e) shows the results of subjective voting of the participants on (a) skin wettedness, (b) perceived exertion, (c) thermal comfort (d) thermal sensation at the head, shoulders and neck, and (e) thermal sensation at trunk during exercise. Skin wettedness was reduced by mean difference 1.25 ± 0.6 ($p = 0.002$) when wearing the vest for both configurations (see Fig. 10(a)). Change in perceived exertion ($p = 0.01$) was improved in V2 compared to V1 and NV tests (see Fig. 10(b)). Finally, thermal comfort ($p = 0.03$), thermal sensation at head, neck, shoulders ($p = 0.03$), as well as, trunk ($p = 0.001$) were improved in both V1 and V2 compared to NV tests (see Fig. 10(c–e)).

The physiological findings of **Group (II)** established a significant effect of the cooling vest (whether V1 or V2) on attenuating ΔT_{cr} by the end of the exercise and recovery period in hot exposure. Furthermore, using V2 provided significant effect in reducing T_{cr} values similar to that of V1 as only the sensate skin of trunk (chest and upper back) was covered. Conductive cooling at the sensate skin of trunk and active vasodilation response at this area enhanced heat dissipation and accelerated thermal regulation in Group (II) (Kenny and Mcginn, 2017). Although insensate skin temperature of the trunk (pelvis and lower back) did not show preserved thermoregulation because its temperature was affected by type of vest (i.e. placement of PCM packets) and therefore had insignificant effect on T_{cr} values. Subjective voting of thermal comfort and sensation supported the physiological responses during exercise in heat because Group (II) was comfortable and slightly

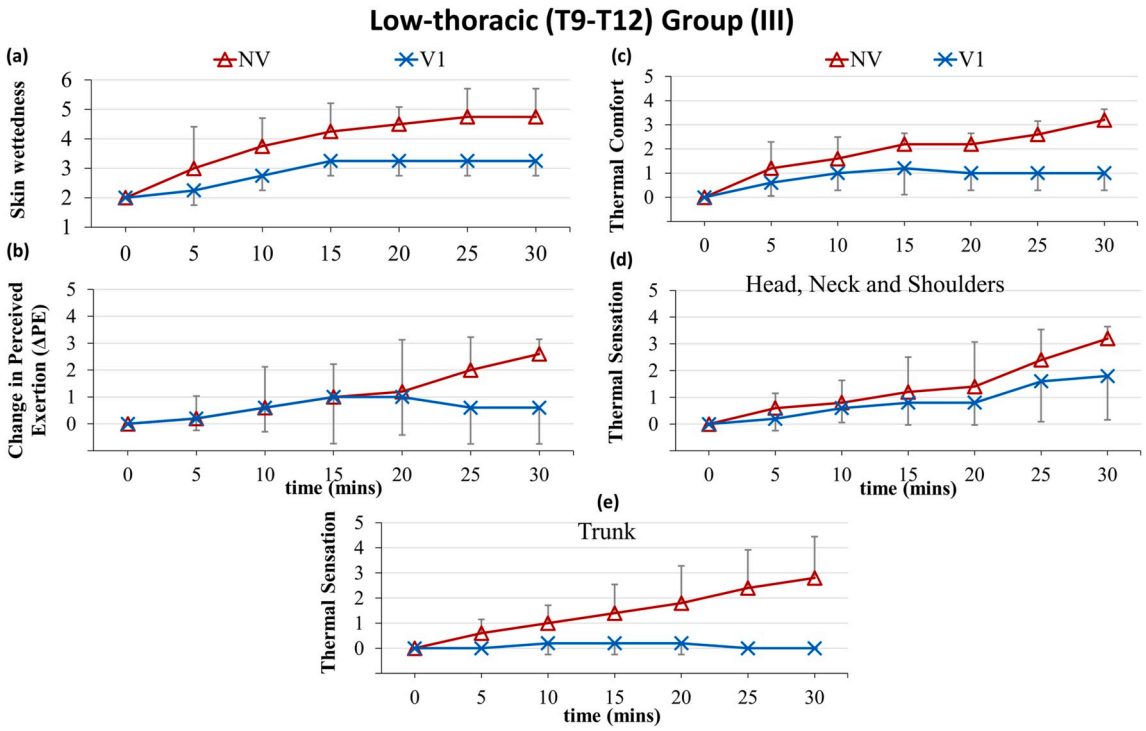

Fig. 13. Plot of (a) skin wettedness (b) ΔPE (change in perceived exertion) (c) thermal comfort (d) thermal sensation at head, neck and shoulders (e) thermal sensation at trunk, for Group (III).

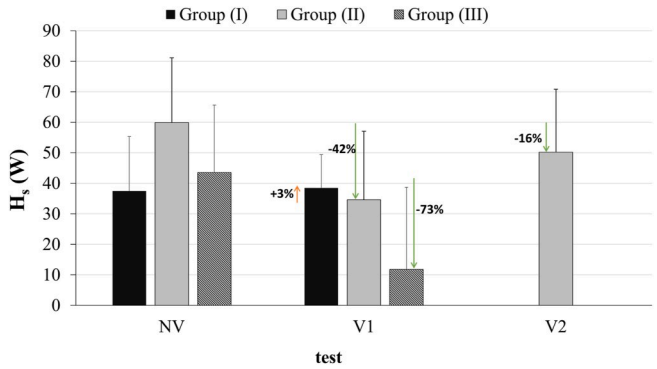

Fig. 14. Plot of stored heat (mean ± SD) for the three PA groups for three tests.

warm when wearing the two types of vest (V1 and V2). However, the lighter weight of V2 compared to V1 (36% less) lessened perceived exertion until the end of the exercise. Therefore, the mid-thoracic group can benefit from the lighter cooling vest that covers the sensate skin of the trunk to limit the unsafe elevation in T_{cr} values during exercise in heat.

4.3. Group III: low-thoracic group (T9-T12)

At time = 0 min, Group (III) showed insignificant difference in the values of *HR*, T_{cr} and $T_{sk,mean}$ between NV and V1 tests (85 ± 12, 89 ± 12 bpm; 37.16 ± 0.3, 37.12 ± 0.3 °C; 31.66 ± 1.3, 31.85 ± 1.0 °C). Fig. 11 (a–c) presents values of *HR*, ΔT_{cr} and $\Delta T_{sk,mean}$ values during the complete 1-h exercise. In Fig. 11(a), *HR* values were lower in V1 compared to NV but this difference was insignificant ($p > 0.05$). Fig. 11(b) shows ΔT_{cr} values for **Group III** during the complete 1-h exercise. There was no change in core temperature during preconditioning while wearing the vest ($\Delta T_{cr} \cong 0.0 \pm 0.07°C$) indicating steady neutral thermal state before exercise. This change started to increase up to $\Delta T_{cr} \cong 0.3 \pm 0.15°C$, $p = 0.034$ followed by a significant decrease in core temperature during recovery period (time = 45 min) in V1 compared to NV. Fig. 11(c) shows ΔT_{sk} values with significant reduction when using V1 compared to NV ($\Delta T_{sk} = 1.00.3°C$, $p = 1.86E - 14$).

No significant difference of T_{sk} values of trunk segments was found at the baseline of the experiment for NV and V1 tests (chest: 33.22 ± 0.73, 33.24 ± 1.29; upper back: 34.10 ± 0.95, 34.21 ± 2.06; pelvis: 33.62 ± 2.21, 32.29 ± 2.18; lower back: 34.71 ± 1.71, 33.60 ± 1.7; $p > 0.05$). Fig. 12(a–d) shows the change in segmental skin temperature (ΔT_{sk}) for the trunk segments (a) chest, (b) upper back, (c) pelvis, and (d) lower back. In Fig. 12(a), the skin temperatures of the chest were less during preconditioning in V1 compared to NV. Yet the difference ΔT_{sk} between the two tests started to be minimal after 5 min of exercising. In Fig. 12 (b), for both tests, the upper back showed a similar trend of transient change during the 1 h. Whereas in Fig.12(c–d), the lower part of trunk (lower back and pelvis) showed a decrease when using V1 during the first 5 min of preconditioning then remained constant throughout the hour.

Fig. 13(a–e) demonstrates the results of subjective voting of the participants on (a) skin wettedness, (b) perceived exertion, (c) thermal comfort (d) thermal sensation at the head, shoulders and neck, and (e) thermal sensation at the trunk during exercise. Skin wettedness was reduced when wearing the vest (see Fig. 13(a)). Change in perceived exertion improved in V1 compared to the NV test ($p = 0.04$) (see Fig. 13 (b)). Finally, thermal comfort, thermal sensation at head, neck, shoulders, as well as trunk, improved in V1 compared to the NV tests ($p<0.05$) (see Fig. 13(c–e)).

The physiological findings of Group (III) showed that people with low-thoracic injury may exhibit thermal physiology similar to that of able-bodied people ($\Delta??_{????,??} \cong 0.42 \pm 0.1$ °C) when performing an upper-body exercise in hot exposure (Young et al., 1987). Furthermore, the use of V1 had a significant cooling effect on diminishing ΔT_{cr} values during exercise and the recovery period. The large sensate skin of trunk (75% of its area) balanced heat gain through active vasodilation at the periphery with cooler blood reaching the core. Thermal comfort and sensation were both improved while wearing V1 during exercise.

Therefore, persons with low-thoracic injury can indeed benefit from a PCM cooling vest covering the sensate skin of trunk (chest, upper back, middle back, and abdomen) to reduce body thermal stress due to exercise in heat.

4.4. Body heat storage

The body heat storage was calculated for a complete 1 h of each test using Eq. (2b) for the three groups, presented in Fig. 14. For **Group I**, H_s was obtained at 37 ± 18 W for NV; 38 ± 11 W for V1. Thus, wearing the vest increased H_s by 3% compared to NV, which confirmed the obtained results of ΔT_{cr}. For **Group II**, H_s was obtained at 60 ± 21 W for NV; 35 ± 22 W for V1; and 50 ± 21 W for V2. It was clear that the stored heat in the body was reduced by 42% with V1 of mass 3.41 kg and 16% with V2 of mass 2.17 kg, compared to NV. This difference between V1 and V2 was due to a higher $\Delta T_{sk,mean}$ value in V2. .For **Group III** H_s was obtained at 44 ± 22 W for NV and 12 ± 27 W for V1 thus covering 34% of the trunk with PCM packets reduced H_s by 73% ensuring the effectiveness of the cooling vest on reducing thermal stress in people with low-thoracic injury.

5. Conclusions

The results of this experimental study indicate that the effectiveness of the PCM cooling vest is correlated to the injury level. The design of V1 showed least effectiveness in reducing core temperature for those with high-thoracic injury. The injury level limited the functional sensory portion of the trunk. Furthermore, both types of the cooling vest achieved the aim of reducing core temperature during recovery, as well as, enhancing thermal comfort in the mid-thoracic group. Furthermore, V2 can be recommended instead of V1 since it provided the same effectiveness but at a lighter weight and coverage area of trunk (36% less). For people with low-thoracic injury level, cooling the sensate skin of the trunk was effective to enhance heat dissipation (73% reduction in stored heat) during exercise and post recovery to accelerate thermal regulation and restore body neutral state. In addition, their thermal state during exercise was comparable to that of able-bodied people.

The drawback of not having persons with complete thoracic SCI was taken into consideration when evaluating the change in core temperature in the NV test. The findings for each group showed a gradual increase in core temperature as an indication of impaired autonomic system in persons with PA. Findings of change in T_{cr} values in NV test were similar to previous studies in literature where recruited participants with complete thoracic injury were asked to perform exercise in hot environmental temperatures (>30.0 °C) (Petrofsky, 1992; Dawson et al., 1994; Price and Campbell, 2003; Trbovich et al., 2016).

Future findings may focus on several approaches for each group. For **Group (I),** other cooling configurations should be evaluated including: (i) locating PCM packets on shoulders, upper chest, and upper back instead of chest, middle back, and abdomen; (ii) using PCM packets at lower melting point; and (iii) using an evaporative cooling vest. For **Group (II),** assessing the PCM cooling vest at lower melting point is recommended to enhance reduction in core temperature during exercise in addition to the recovery period. Using an evaporative vest can also be evaluated for **Groups (II)** and **(III)**.

CRediT authorship contribution statement

Farah Mneimneh: Formal analysis. **Charbel Moussalem:** Formal analysis. **Nesreen Ghaddar:** Conceptualization, Writing - review & editing. **Kamel Ghali:** Conceptualization, Methodology, Investigation. **Ibrahim Omeis:** Supervision.

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