Journal of Thermal Biology 82 (2019) 123–141

Contents lists available at ScienceDirect

Journal of Thermal Biology

journal homepage: www.elsevier.com/locate/jtherbio

Would personal cooling vest be effective for use during exercise by people with thoracic spinal cord injury?

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ARTICLE INFO

Keywords:
Thoracic spinal cord injury
Paraplegia
Thermal response
Cooling vest
Bioheat model

ABSTRACT

People with thoracic spinal cord injury (SCI), named people with paraplegia (PA), are vulnerable to thermal heat stress during exercise due to disruption in their thermal physiology. Using personal cooling vests with phase change material (PCM) or ice presents a possible solution for PA to suppress the increase in core temperature and body heat storage. With the limited published experimental studies about effective cooling vest for PA, this work aims to develop an altered PA bioheat model combined with cooling vest model to study cooling vest performance during exercise. The integrated PA bioheat and vest models predict core and skin temperatures, latent and sensible heat losses and change in body heat storage for PA with and without a cooling vest. The models were validated with published experimental data on PA without the cooling vest and on PA with two cooling vests; one using PCM at melting temperature of 15 °C and the other using ice packets during exercise. It was observed that sensible heat losses at the four torso segments (abdomen, lower back, chest and upper back) increased with the vest case compared to the *no-vest* case; while, latent heat losses decreased compared to the *no-vest* case. However, insignificant change was seen in core temperatures and body heat storage as was also reported experimentally. The performance of each of the cooling vest during exercise on PA was dependent on skin coverage area and melting temperatures.

1. Introduction

People with spinal cord injury (SCI), as they age, are at a great risk of health threatening diseases such as heart disease, diabetes, pressure sores, lung problems, muscle atrophy, joint contractures and pain (Whiteneck et al., 1992). The greater health risk associated with SCI increases with the higher level of injury and its severity whether complete or incomplete (Kirshblum et al., 2011). Therefore, SCI is a major public health concern which promotes the implementation of motivational programs for this population to maintain an active lifestyle (Simpson et al., 2012; Munce et al., 2013). One of the motivational awareness strategies is exercise. People with SCI can adapt to a level of physical activity at which an exercise is performed at metabolic rate MET > 4 to reduce the risk of health conflicts (Kehn and Kroll, 2009; Melo et al., 2018). Exercising can improve the quality of life for people with SCI, mainly for people with thoracic (T1-T12) and lumbar (L1-L5) SCI or what is defined as paraplegia. People with paraplegia (PA) having injury level above T5 (T6-T12) preserve **active** sensory and motor functions in the segments above injury level same as able-bodied people (AB): **fingers, palms, upper arms, forearms, chest, upper back, neck and head**. Whereas, their sensory and motor functions are disrupted in the segments below injury level: **feet, calves, thighs, abdomen, and lower back**. The active sensory body segments (non-paralyzed) are related to the spinal cord vertebrae above injury level; while, the inactive sensory body segments (impaired) are related to the spinal cord vertebrae below injury level. Thus, PA can depend on the body segments with active sensory to participate in daily strength exercises and flexibility for sake of reducing health complications and improving muscular strength of active body parts (Kehn and Kroll, 2009; Melo et al., 2018).

Despite the importance of exercising, PA may encounter barriers to exercise related to thermal stress at high metabolic rates that forces PA to stop the exercise because they are no longer thermally comfortable (Scelza et al., 2005). Thermal stress is defined by an increase in core temperature above body thermal neutral state (36.8 ± 0.5 °C) and imbalance of body heat storage with the surrounding ambient condition. This thermal disturbance is a major consequence of SCI due to the dysfunction of thermoregulatory responses which include vasodilatation (dilation of blood vessel) and sweating for body segments below injury level (Attia and Engel, 1983; Petrofsky, 1992; Wilsmore, 2007).

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https://doi.org/10.1016/j.jtherbio.2019.04.004
Received 11 January 2019; Received in revised form 8 March 2019; Accepted 9 April 2019
Available online 13 April 2019
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Nomenclature

A	Area (m^2)
AB	healthy and able-bodied humans
AD	arterial diameter
BMR	basal metabolic rate
CO	cardiac output
EE	energy expenditure
FM	fat mass
H_{stored}	the rate of change in body heat storage (W)
HP	People with high thoracic SCI
LBM	lean body mass
LP	People with low thoracic SCI
P_{skin}	vapor pressure at the skin (Pa)
PA	people with paraplegia
PCM	phase change material
R_d	dry resistance (m^2·°C/W)
R_e	evaporative resistance (m^2·kPa/W)
RH	relative humidity (%)
SBP	skin blood perfusion flow
SCI	spinal cord injury
SFT	skin fat thickness (m)
T_{core}	core temperature (°C)
T_{skin}	skin temperature (°C)

The PA thermoregulatory disruption reduces the amount of released heat from the core to the skin (Petrofsky, 1992); thus, higher core temperature (T_{core}) values are expected to occur for PA. This may bring a multitude of potential issues such as the reduction of cellular function and organismal survival or the increase of acute and chronic health risks for these patients (Cheung et al., 2016). On the other hand, skin temperature (T_{skin}) values are normally higher at the body parts above SCI level than those below injury level because the latter lacks skin blood perfusion although sensate and insensate skin is exposed to same environmental conditions (Price and Campbell, 1997). As a result, PA are not able to maintain a constant T_{core}. Then, the PA physical performance and perceived exertion are reduced at moderate and high metabolic rates or when exposed to moderate or hot climates.

Experimental studies in literature reported that PA are vulnerable to serious heat stress problems during exercise if precautions are not adopted (Griggs et al., 2014). One of the preventive ways is the use of personal cooling method such as wearing a cooling vest that can be an assistive technique for the body to release heat to the surrounding and reduce stored energy without hindering body movements (Griggs et al., 2014; Bongers et al., 2015). When using a cooling vest at the PA torso skin area, T_{skin} values at this skin site can be reduced to increase conduction heat transfer from the hot core to the cold skin; yet, convection heat transfer due to skin blood perfusion is **insignificant** at the body segments below injury level. Thus, when wearing a cooling vest, sensible heat losses may be greater at torso segments above injury level than the losses from the segments below injury level. The performance of several types of cooling vests, such as phase change material (PCM) cooling vest, ice vest, and evaporative cooling vest, was reported in literature based on PA human subject tests during exercise at different ambient conditions (Griggs et al., 2014; Bongers et al., 2015). Published experimental results showed insignificant reduction in T_{core} value of **PA** with cooling during exercise, yet measured segmental T_{skin} values of the torso area (coverage area by the vest) were lower with cooling during exercise (Griggs et al., 2014; Bongers et al., 2015).

Nevertheless, the above studies have not focused on the cooling vest design for improving its performance while taking into consideration the altered physiology and the lack of thermoregulatory responses at the PA body segments that are below the injury level. In addition, the empirical literature had limitations in recruiting participants with similar injury level and severity of injury; thus, increasing error within subjects. In addition, the number of published studies evaluating the performance of PA during exercise with personal cooling techniques is still limited (Griggs et al., 2014; Bongers et al., 2015). Hence, it was not possible to determine whether cooling the sensate skin area of the active torso segments is more effective than cooling the whole torso skin area to increase sensible heat losses during exercise and reduce T_{core} value in PA. To overcome the experimental barriers and improve cooling vest design for PA, it is of interest to develop a robust mathematical PA bioheat model that can predict T_{core} and T_{skin} values as well as segmental latent and sensible heat losses of PA. This would reduce the need to perform extensive experiments on PA during exercise to test the effectiveness of different cooling vest designs on body thermal state.

Several published modelling studies included the integration of personal cooling methods that used vests with phase change material (PCM), fans or combinations of fans and PCM with a bioheat model for AB (Hamdan et al., 2016; Itani et al., 2016; Bachnak et al., 2018). These integrated models were reported to be robust in predicting the human thermal response with cooling at warm/hot climate and moderate/high activity level. They were validated by experimental studies on healthy AB performing exercise in warm climate (Hamdan et al., 2016; Itani et al., 2016; Bachnak et al., 2018). Results showed that the PCM cooling vest performance for AB varied according to vest design including PCM coverage area, arrangement, and melting temperature as well as fan speed when operated, climate condition and physical activity level. However, since the thermophysiology of PA is disrupted after SCI compared to that of AB, conventional cooling methods may not be affective on PA in a way similar to that of AB. it is of interest to develop an altered PA bioheat model and integrate it with the published cooling vest models to predict the PA thermal response and effectiveness of the cooling intervention. Mneimneh et al. (2018) developed an altered bioheat model for people with tetraplegia (TP) who have the SCI in the cervical vertebrate above thoracic vertebrae (C1−C7). They modified the AB bioheat model of Salloum et al. (2007) and accounted for changes in circulatory system of the body parts below injury level, energy expenditure and thermoregulatory responses reported in literature. Therefore, a similar approach is followed in this work to develop a PA bioheat model and combine it with published models of PCM cooling vests used for enhancing performance of active AB in hot climate (Hamdan et al., 2016; Itani et al., 2016).

Therefore, to enhance the effectiveness of personal cooling vest, this work aims at developing a combined PA bioheat model with cooling vest model and evaluate the possibility of increasing sensible heat losses at the torso skin to reduce T_{core} in PA during exercise. The PA bioheat model is validated with published experimental results on PA core and segmental skin temperatures. Then, the integrated PA Bioheat and cooling vest model is validated with available published experimental data for active PA wearing cooling vests (Armstrong et al., 1995; Trbovich et al., 2014). Since the combined PA bioheat model with cooling vest model would predict T_{core} and T_{skin} of PA as well as segmental heat losses with and without the cooling method, the data is used to explain the empirical results and the means to improve the cooling vest design by taking into consideration the altered physiology in the body segments below injury level and hence enhance cooling effect on the active PA.

2. Problem statement

The purpose of this study is to recommend means of enhancing cooling for PA to regulate their T_{core} values and body heat storage during exercise. These means require understanding of the changed physiology and its impact on core and skin temperatures as well as sensible and latent heat losses at the torso parts, above and below injury

level, with and without trunk cooling interventions. The focus on the trunk is because it contains the critical body organs and generates the most heat of the body (Salloum et al., 2007; Karaki et al., 2013).

To predict thermal responses of PA at different climates and activity levels without cooling interventions, the Mneimneh et al. (2018) TP bioheat model was modified to reflect changes in physiology and thermoregulatory responses of impaired body segments. The altered PA bioheat applies for non-athletic paraplegic patients with ***thoracic injury level*** T6 -T12. Fig. 1a shows the twelve thoracic spinal cord vertebrae (T1-T12) in the human body; each responsible for a body segment motor and sensory function. For example, any patient having injury between T1-T5 has an impairment at the upper chest, mid back, and abdominal muscles (Sekhon and Fehlings, 2001; Cremin, 2011). Whereas, patient having injury between T6-T12 has an impairment only at the abdominal and back muscles (Sekhon and Fehlings, 2001; Cremin, 2011). Thus, higher thoracic SCI (T6-T12) would qualify the individual to use manual wheelchair and maintain good body control in seated position (Sekhon and Fehlings, 2001; Cremin, 2011). The attributed sensory and motor function for injury level between T6 and T12 was taken in to consideration when modifying Mneimneh et al. (2018) TP bioheat model.

In the PA model, the human body was divided into 31 segments as that of Mneimneh et al. (2018) bioheat model: fingers, palms, forearms, upper arms, chest, pelvis, thighs, calves and feet. Each segment was subdivided in to four nodes: core, skin, artery and vein, and covered by a fabric layer at the skin node as shown in Fig. 1b. Note that the skin node for the trunk segments (chest and pelvis) and thighs is divided into four nodes to take into consideration any non-uniformity in the environment adjacent to these surfaces (Al-Othmani et al. 2008). For the cooling purposes, PA were supposed to be a wearing a sleeveless vest that covered the upper back, chest, lower back and abdomen to cover the maximum possible skin area of the torso having highest metabolic rate.

In the current work, the ice cooling vest (melting point of 0 °C) and PCM cooling vest (melting point of 15 °C) are integrated with the PA bioheat model. The selection of these two vests was based on availability of published experimental studies reporting the effect of cooling on T_{core} of the PA at specified room temperature, relative humidity and duration of activity (Armstrong et al., 1995; Trbovich et al., 2014). The models (Fabric-PCM-PA model and fabric-ice-PA model) are used also to predict sensible and latent heat losses of PA during exercise to provide additional insight on the reported experimental results and assess the cooling effectiveness of each type of vest on PA (Armstrong et al., 1995; Trbovich et al., 2014).

3. Modelling methodology

The development of PA Bioheat model and integration of cooling methods were achieved through systematic approach as follows: (i) extract data about physiological and thermoregulatory changes of the body in PA compared to that of AB; (ii) use extracted data to modify the published model of TP to be applicable for PA; and finally, (iii) integrate the two published phase change material and ice cooling vest models (Armstrong et al., 1995; Trbovich et al., 2014) to the PA bioheat model to assess the effectiveness of cooling on PA during exercise.

The alterations in the human body after thoracic SCI included: (i) body composition as lean body mass (LBM) and skin fat thickness (SFT), (ii) threshold temperatures of vasomotor, sudomotor and shivering,

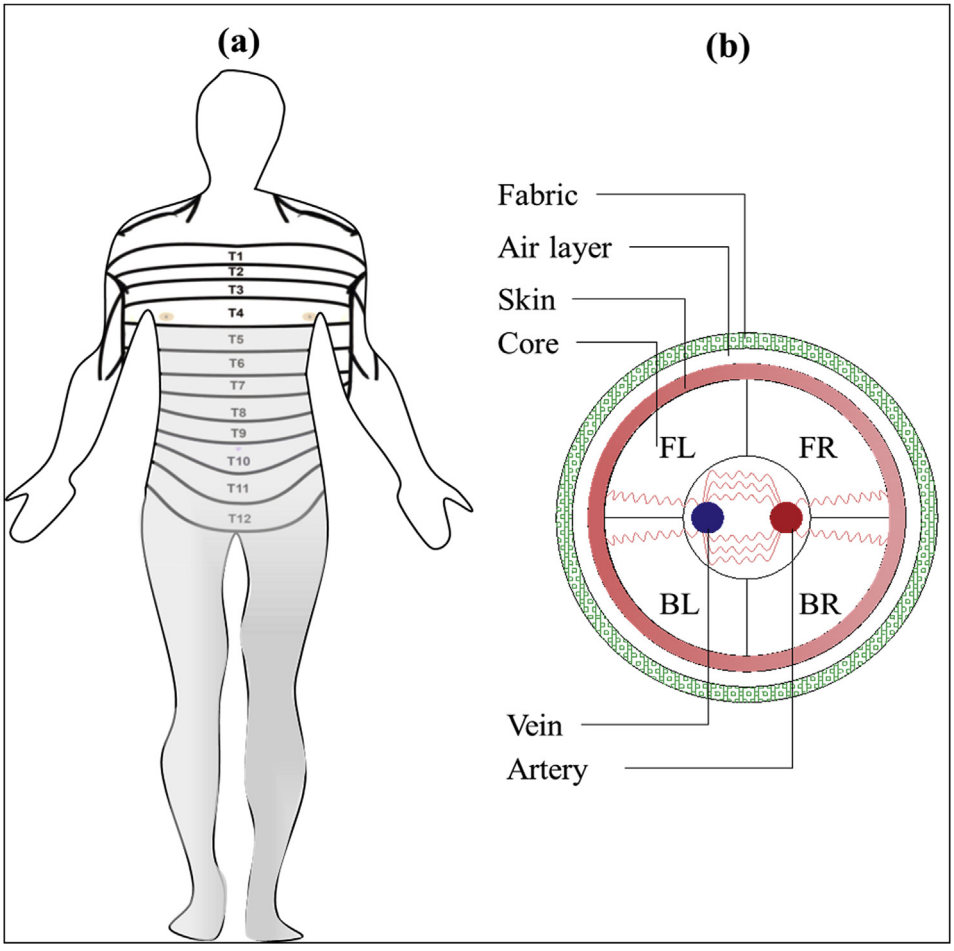

Fig. 1. Schematic illustration of (a) thoracic SCI (T1-T12) (b) nodal section of body segment.

Table 1
Segmental core, skin and total basal metabolic rates in Watts for AB and PA (Spungen et al., 2003; Salloum et al., 2007).

Body Part	AB (Salloum et al., 2007)			Ratio of LBM in PA compared to AB ($\frac{LBM_{PA}}{LBM_{AB}}$)	PA Thoracic Level (T1-T12)		
	BMR_{core} (W)	BMR_{skin} (W)	$BMR_{Total} = BMR_{core} + BMR_{skin}$ (W)	Spungen et al. (2003)	$BMR_{PA,core} = BMR_{AB,core} \times \frac{LBM_{PA}}{LBM_{AB}}$(W)	$BMR_{PA,skin} = BMR_{AB,skin}$ (W)	$BMR_{Total} = BMR_{core} + BMR_{skin}$ (W)
				Body segments above injury level for PA			
Head	18.43	0.22	18.65	100%	18.43	0.22	18.65
Chest	5.95	0.60	6.55	98%	5.82	0.60	6.42
Left/Right upper arm	1.06	0.18	1.24	102%	1.08	0.18	1.26
Left/Right forearm	0.59	0.10	0.69	102%	0.6	0.10	0.70
Left/Right hand	0.095	0.09	0.19	102%	0.096	0.09	0.19
				Body segments below injury level for PA			
Pelvis	46.86	0.60	47.46	98%	45.82	0.60	46.42
Left/Right thigh	1.70	0.34	2.04	58%	0.98	0.34	1.32
Left/Right calf	0.75	0.15	0.90	58%	0.43	0.15	0.58
Left/Right foot	0.14	0.12	0.26	58%	0.08	0.12	0.20
***BMR_{Total}* (W)**	79.91	3.39	**83.30**	–	76.6	3.39	**80.00**
Reported Data in Literature for BMR in PA compared to AB							
Buchholz et al. (2003)			**81.2 ± 10.82**				**71.3 ± 11.04**
Nightingale and Gorgey, 2018			NA				**72.64 ± 7.85**

Mean ± SD; Abbreviations: LBM: lean body mass; BMR: basal metabolic rate; PA: paraplegic people; AB: able-bodied people; W: watts; NA: not available.

and, finally, (iii) cardiovascular functions including arterial diameter (AD) and cardiac output (CO). These alterations were incorporated in the bioheat model for TP of Mneimneh et al. (2018) to predict overall and segmental skin and core temperatures for PA at different climate conditions and activity levels. In addition, segmental heat losses have been predicted for thermally active and inactive segments.

Then, the PA bioheat model is integrated with robust cooling vest models for PCM vest and ice vest reported in literature (Itani et al. and Hamdan et al.). The following subsections describe the main modelling features for developing the bioheat model for PA and integration of the two types of cooling vests: PCM vest and ice vest.

3.1. PA Bioheat model

The physical and physiological changes in the body after SCI at thoracic vertebrae were related to the anatomy, physiology and thermoregulatory functions of **PA** compared to that of AB. These changes were applied for the sensory inactive body segments including feet, calves, thighs, lower back and abdomen because as mentioned previously this model applies for PA with thoracic injury above T5 (T6-T12) (Sekhon and Fehlings, 2001; Cremin, 2011). The sensory active body segments including head, neck, upper back, chest, upper arms, forearms, palms and fingers maintain similar characteristics and thermoregulatory functions as that of AB. These specifications about injury level and its severity were taken into consideration for development of the bioheat model for PA.

Sensory inactive body segments lose muscular mass and gain fat leading to reduction in energy expenditure (EE). Although there is increase in fat mass, the sensory active segments above injury level have an increase in muscular mass mainly for the arms because of their extra usage for **Mat** mobility (***ability to change position independently in supine position***) and wheelchair movement ***(ability to balance seating position)***; thus, causing an increment in EE (Spungen et al., 2003). Moreover, the impact of SCI on blood vessels structure is observed by the decrement in arterial diameter (AD) for segments below injury level which increases with injury duration (Groot, 2005). Whereas, AD increases segments above injury level due to increased muscular use. Therefore, the model assumes that arterial blood flow is reduced for the segments below injury level and increased for those above injury level. Adding to the above, the thermoregulatory responses which include vasomotor (vasodilation and vasoconstriction), sudomotor (sweating) and shivering are also affected after SCI in **PA**; they are totally disrupted for segments especially for an injury **located at or below T10**; while they remain activated for segments above this injury level. This means that skin blood perfusion *(SBP)* and blood flow rates are constant for the lower body including feet, calves, thighs, abdomen and lower back; also, no perspiration or shivering are observed at these segments (Cooper et al., 1957). Following the approach reported in Mneimneh et al. (2018) of the TP bioheat model, the detailed quantitative and qualitative changes for the body segments below injury level for PA were extracted from reported experimental studies for PA. Whereas, for the body segments above injury level, the AB physiology and thermoregulatory responses were applicable for them.

Energy Expenditure: Body segments below injury level are susceptible to muscle atrophy defined as the loss of LBM and transformation of muscle fibres to a less metabolically active type characterized as fat vacuoles (Biering-Sørensen et al., 2009). Consequently, their EE is decreased compared to that of AB even at very low activity level (at rest). Contrarily, **PA** upper body segments mainly arms undergo increase in LBM and EE due to continuous use of arms for Mat mobility and wheelchair movement (Spungen et al., 2003). Moreover, since subcutaneous skin fat thickness (SFT) is dependent on the caloric intake of the body, it is expected to increase in all body parts because of overall reduced physical activity after injury. Whereas, the head and neck maintain similar LBM and SFT to that of AB, and of course similar EE (Spungen et al., 2003). The variation of SFT in **PA** has direct effect on the heat transfer between the core and skin nodes, rather than skin basal metabolic rate (BMR). Thus, the thermal conductance of the fat-skin layer and the body part itself decreases as they are correlated in Eqs. (1a)–(1c) (Mneimneh et al., 2018):

$$\frac{1}{K} = \frac{1}{K_{muscle}} + \frac{1}{K_{fat-skin}} \tag{1a}$$

$$K_{muscle} = \frac{A_{skin}}{0.05} \tag{1b}$$

$$K_{fat-skin} = \frac{A_{skin}}{0.0048(th_{fat+skin} - 2) + 0.0044} \tag{1c}$$

In Table 1, the segmental core and skin basal metabolic rates were calculated for **PA** based on values of BMR used in Salloum et al. model (2006) for AB. Reported data in literature about ratio of LBM in **PA** compared to that of AB ($\frac{LBM_{PA}}{LBM_{AB}}$) for each body segment was obtained and multiplied by its corresponding core BMR of AB ($BMR_{AB,core}$) for the same segment (Spungen et al., 2003; Salloum et al., 2007). Then, the obtained value was the core BMR for **PA** at this segment ($BMR_{PA,core}$). It is noted that the skin BMR for **PA** was considered the same as for AB, and the total BMR was the sum of both skin and core BMR at this segment. Conduction heat transfer between the skin and core is reduced as the thermal resistance increases exposing the body to excessive heat stress especially in warm ambient conditions. Therefore, in the altered bioheat model for **PA**, new values of SFT were calculated as summarized in Table 2, where they were obtained by multiplying the ratio of SFT in **PA** to AB ($\frac{SFT_{PA}}{SFT_{AB}}$) by the SFT of AB (Salloum et al., 2007).

Variability of core temperature thresholds in PA: It was reported in literature that **PA** may reach a stable core temperature like that of AB usually at 36.8 ± 0.2 °C, but non-uniform distribution of skin temperature when exposed to neutral ambient conditions at a room temperature of range 22–25 °C and relative humidity (RH) 45–50% (Attia and Engel, 1983). However, major deviations from the thermal steady state of the body is expected to occur in **PA** as the core temperature may change in a rate higher than of AB when exposed to extreme environmental conditions (Attia and Engel, 1983; Wilsmore, 2007). Consequently, the partly poikilothermic behaviour of **PA** disposes the body to undesirable thermal stress which itself may be a life-threating disorder for body cells and enzymes (Cheung et al., 2016). Similar to the list of thermoregulatory threshold parameters for TP compared to AB presented in Mneimneh et al. (2018), Table 3 summarizes altered PA threshold values of T_{core} **PA** based on reported data in literature (Salloum et al., 2007; Wilsmore, 2007). The disruption of

Table 2
Segmental skin fat thickness (SFT) of AB and PA (Spungen et al., 2003; Salloum et al., 2007).

Body element	AB (Salloum et al., 2007)	PA	Ratio of SFT in PA compared to AB (Spungen et al., 2003)
	SFT (mm)	SFT (mm)	$\frac{SFT_{PA}}{SFT_{AB}}$
		Body segments above injury level	
Head + Neck	8.5	8.50	100%
Chest	19.12	22.87	120%
Left/Right upper arm	4.51	8.94	198%
Left/Right forearm	4.51	8.94	198%
Left/Right hand	7.4	14.66	198%
		Body segments below injury level	
Pelvis	19.12	22.87	120%
Left/Right thigh	10.64	14.89	140%
Left/Right calf	10.64	14.89	140%
Left/Right foot	11.7	16.37	140%

Table 3
Threshold values of vasomotor, sudomotor and shivering responses for PA compared to AB (Salloum et al., 2007; Wilsmore, 2007).

Thermoregulatory Action	Threshold Control Parameter	PA	AB
Sweat Onset	T_{core}	37.1 ± 0.2 °C (Wilsmore, 2007)	37.2 °C (Salloum et al., 2007)
Basal Thermal Condition	T_{core}	36.8 ± 0.9 °C (Attia and Engel, 1983)	36.8 °C (Salloum et al., 2007)
Shivering Onset	T_{core}	35.12 ± 0.91 °C (Wilsmore, 2007)	35.8 °C (Salloum et al., 2007)
	T_{skin}	–	35.5 °C (Salloum et al., 2007)
Maximum Shivering	T_{core}	35.0 ± 0.5 °C (Wilsmore, 2007)	33.0 °C (Salloum et al., 2007)

Mean ± Standard deviation. Abbreviations: PA: paraplegic people; AB: able-bodied people; SFT: skin fat thickness.

Table 4
Cardiac output values at the basal, maximum and minimum demands in **PA** compared to AB (Salloum et al., 2007; Wijnen et al., 1991; Schmidt-Trucksäss et al., 2000; Groot et al., 2006).

Body part	Basal (cm^3/hr)		Maximum (cm^3/hr)		Minimum (cm^3/hr)	
	AB	PA	AB	PA	AB	PA
Head	55,119	55,119	63,408	63,408	53,910	53,910
Neck	1407	1407	3620	3620	1084	1084
Torso	198,164	198,164	247,650	247,650	190,947	190,947
Right or Left Upper Arm	3852	3852	11,261	11,261	2772	2772
Right or Left Forearm	2151	2151	7196	7196	1415	1415
Right or Left Hand	1378	1378	4718	4718	891	891
Right or Left Thigh	6196	*4779*	17,193	*4779*	4592	*4779*
Right or Left Calf	2741	*2116*	10,344	*2116*	1632	*2116*
Right or Left Foot	1339	*1219*	5683	*1219*	706	*1219*
Total CO (cm^3/hr)	290,005	**285,682**	427,468	**377,258**	269,957	**272,327**
Total CO (cm^3/hr) for **PA** reported in Literature						
Kessler et al. (1987) (Mean ± standard deviation in cm^3/hr.)	323,353 ± 83,832	353,293 ± 53,892	–	–	–	–
Jehl et al., 1991 (Mean ± standard deviation in cm^3/hr.)	–	–	461,078 ± 83,832	449,102 ± 53,892	–	–

Abbreviations: PA: paraplegic people; AB: able-bodied people; CO: cardiac output.

Table 5
SWEAT and COLD weighting factors for body segments above injury level of PA defined in the bioheat model (Fitzgerald et al., 1990; Salloum et al., 2007; Wilsmore, 2007).

Body Segment	Head	Chest	Upper Back	Upper arm	Forearm	Palm	Finger
SWEAT	0.1215	0.275	0.275	0.0444	0.0326	0.093	0.00155
COLD	0.0775	0.515	0.515	0.0024	0.0014	0.0001	0.00002

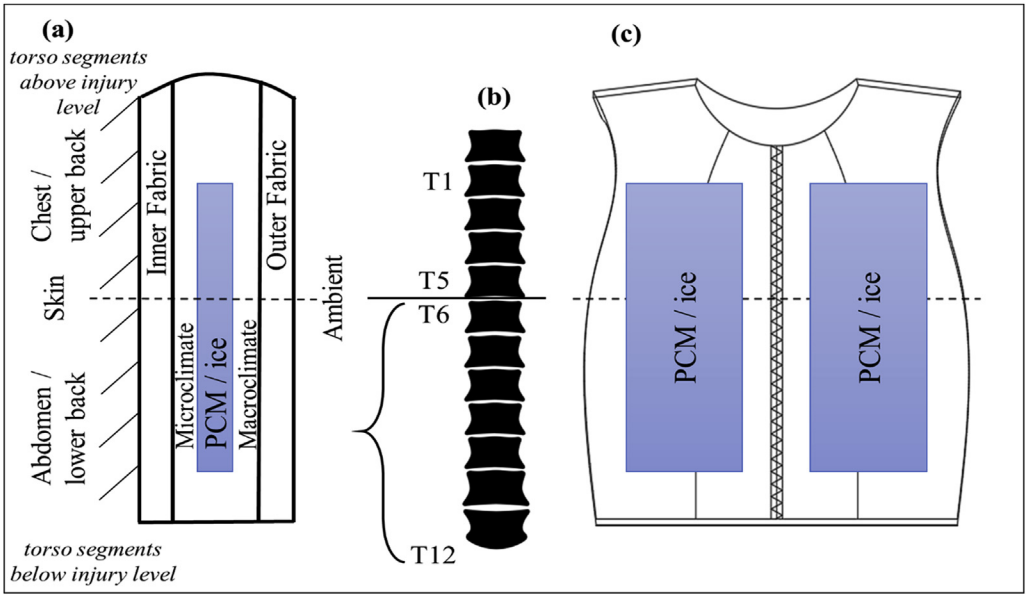

Fig. 2. Schematic of a cooling vest with PCM or ice packets covering skin area at the impaired segments (abdomen and lower back), and active segment (upper back and chest): (a) side view of different layers of fabric-PCM or fabric-ice, (b) spinal cord injury level related to PA (T6-T12) bioheat model, (c) front view of the vest with the packets.

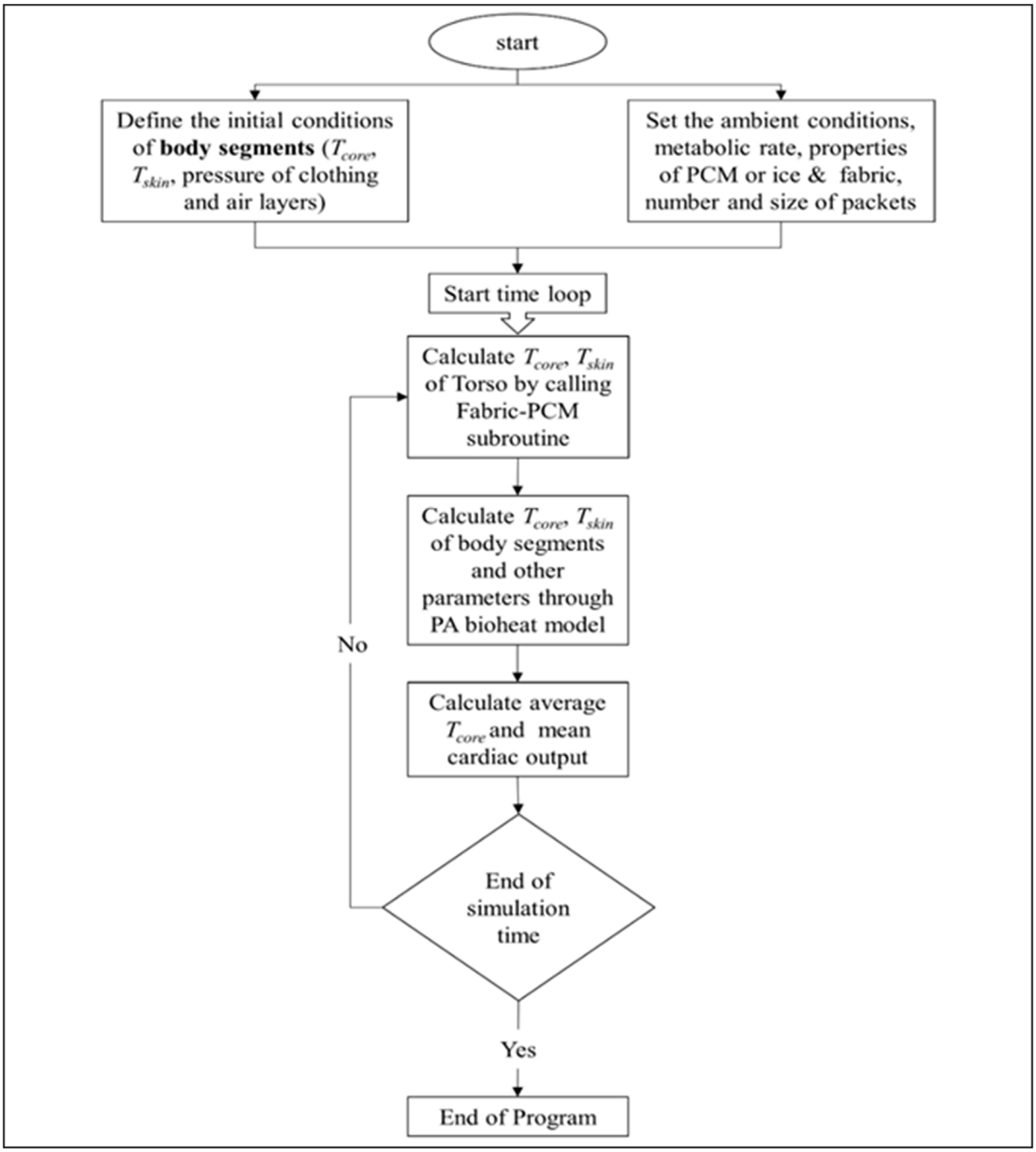

Fig. 3. Flow chart of numerical methodology of integrated PCM or Ice vest with PA bioheat model.

thermoregulation in **PA** for segments below injury level shifted threshold values of both sudomotor and shivering responses for sensate skin area, yet the vasomotor onset temperature was still considered to be the same as that of AB for segments above injury levels at the basal thermal condition (Attia and Engel, 1983; Wilsmore, 2007).

Alterations in blood vessel diameter because of paraplegia: The blood circulatory system undergoes alterations in structure and distribution because of paraplegia. The blood vessels' structure is reformed at early stage of injury during which the arterial diameter is decremented for those below injury level, yet no change for the blood vessels above injury level (Olive et al., 2002; Groot, 2005; Groot et al., 2006) . The rate of change of blood vessel diameter in **PA** was correlated to the injury level and its severity (Dawson et al., 1994; Mathias, 2006; Popa et al., 2010; West et al., 2012). Subsequently, the drop of arterial diameter in **PA** is part of the body total adaptation to the paraplegic condition. Quantitatively, it was reported in literature that the arterial diameter was reduced by 30% for the blood vessels below injury level; thus, affecting the blood flow for the corresponding body parts (Wijnen et al., 1991; Schmidt-Trucksäss et al., 2000; Groot et al., 2006). This reduction was implemented in the altered bioheat for **PA** for the blood vessels in the back, abdomen, thighs, calves and feet. For the veins, its dimension is almost twice the radius of the artery having the same index (Salloum et al., 2007). The same was assumed for the superficial vein (Groot, 2005; 2006a).

The cardiac output and heart rate: The consequence of arterial structure remodelling after SCI is the resulting segmental arterial or regional blood flow rate changes in body parts below injury level. Yet, the overall value of CO in **PA** showed insignificant difference from than

Table 6
Criteria of experimental studies of Attia and Engel (1983) and Price and Campbell (1997, 2003).

Experiment	Reference	sample size (injury level)	Activity level and duration	Climatic conditions	Measured variable	Clothing
1) Seated at rest in steady state thermal condition	Attia and Engel (1983)	n_{PA} = 9 (L1-T5) n_{AB} = 6	Seated at rest 45 min	15, 20, 25, 30, 35, 40 °C Relative humidity 45%	Rectal temperature (T_{core}) T_{skin} of upper arm, lower arm, upper leg, and lower leg	light summer clothing (≃0.4 clo)
2) Arm-crank exercise in moderate environmental conditions	Price and Campbell (1997)	n_{PA} = 10 (T3/4-L4) nAB = 9	arm-crank exercise at intensity of 80% peak heart	21.5 (1.7)°C Relative humidity 47.0 (7.8) %.	Aural temperature Tcore forehead, chest, and thigh T_{skin}	light weight tracksuit trousers and training shoes
3) Arm-crank exercise in hot environmental conditions	Price and Campbell (2003)	nLP = 10 (T7 and below) nHP = 10 (T1-T6)	arm-crank exercise at intensity of 60% oxygen uptake	31.5 ± 1.7 °C Relative humidity 42.9 ± 8.0%.	Aural temperature T_{core} back and thigh T_{skin}	light weight tracksuit trousers and training shoes with no clothing covering the upper body

Abbreviations: PA: paraplegic people; AB: able-bodied people; LP: people with low thoracic SCI; HP: people with high thoracic SCI.

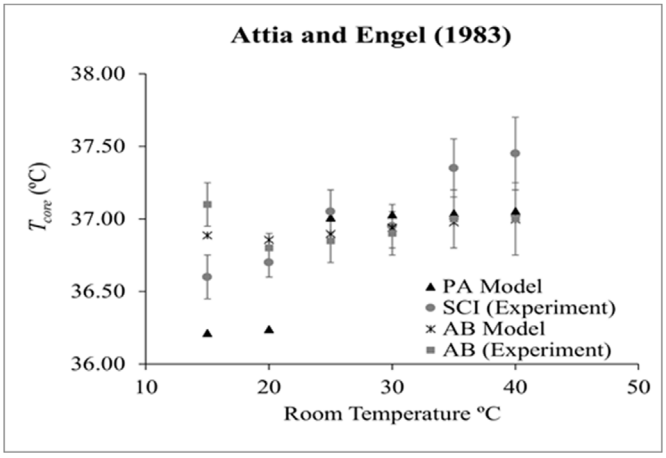

Fig. 4. Scatter plot of predicted values and experimentally measured mean (± standard deviation) values of T_{core} for both groups PA and AB seated at rest at different room temperatures and relative humidity 45% (Attia and Engel, 1983).

that of AB (Kessler et al., 1987; Hopman et al., 1993; Takahashi et al., 2005). CO defined as the blood volume pumped per minute is a cardiovascular indicator for the heart rate (HR) and stroke volume (SV) (Dampney, 1994). In general, SV is lower in **PA**, yet it follows the same pattern as SV in AB mainly during incremental exercise, i.e. an increase in SV until reaching 45–50% of peak of worked exercise and thereafter a stable SV. In order, to use CO correlations defined in Eqs. (2a)–(2c) (Mneimneh et al., 2018), new values of basal, maximum and minimum CO values were obtained by applying reduction of arterial blood vessel structure on CO values of AB (Salloum et al., 2007) as presented in Table 4. These values were validated by referring to reported data in literature (Kessler et al., 1987; Jehl et al., 1991).

$$CO = \frac{CO_{dil} \times CO_{con}}{CO_{basal}} \tag{2a}$$

$$CO_{dil} = \begin{cases} CO_{basal}\ for\ T_{cr} \le T_{cr_threshold}\,^{\circ}C \\ \frac{T_{cr} - T_{cr_threshold}}{38.2 - T_{cr_threshold}}(CO_{max} - CO_{basal}) \\ \quad + CO_{basal}\ for\ T_{cr_threshold}\,^{\circ}C < T_{cr} < 37.3^{\circ}C \\ CO_{max}\ for\ T_{cr} \ge 37.3^{\circ}C \end{cases} \tag{2b}$$

$$CO_{con} = \begin{cases} CO_{min}\ for\ T_{cr} \le 35.12^{\circ}C \\ \frac{T_{cr} - 35.6}{T_{cr_threshold} - 35.6}(CO_{basal} - CO_{min}) \\ \quad + CO_{min}\ for\ 35.12^{\circ}C < T_{cr} < T_{cr_threshold}\,^{\circ}C \\ CO_{basal}\ for\ T_{cr} \ge T_{cr_threshold}\,^{\circ}C \end{cases} \tag{2c}$$

Skin blood perfusion: It is one of the body thermoregulatory responses to the change in T_{core} to maintain a stable T_{core}. However, this thermoregulatory response is disrupted in PA for the body segments below injury level including thighs, calves, feet, lower back and abdomen with a percentage of reduction of 12% in SPB compared to that of AB (Hogancamp and Everett, 2004). When SBP becomes constant independent of body thermal state, it induces blood pooling in the lower body extremities and increase of T_{core} of PA due to inability to redistribute blood to the active muscles in the body especially during exercise (Dawson et al., 1994; Mathias, 2006; Popa et al., 2010; West et al., 2012). Whereas, for the segments above injury level mainly the forearms, it is observed to have an increased SBP with a ratio of 3.296 compared to that of AB (Hogancamp and Everett, 2004). The remaining active body segments (fingers, upper arms, palms, chest and upper back) maintain similar values to that of AB. Three values of SBP (basal, minimum and maximum values) were modified for the thighs, calves, feet, abdomen, lower back and forearms (Mneimneh et al., 2018). Then,

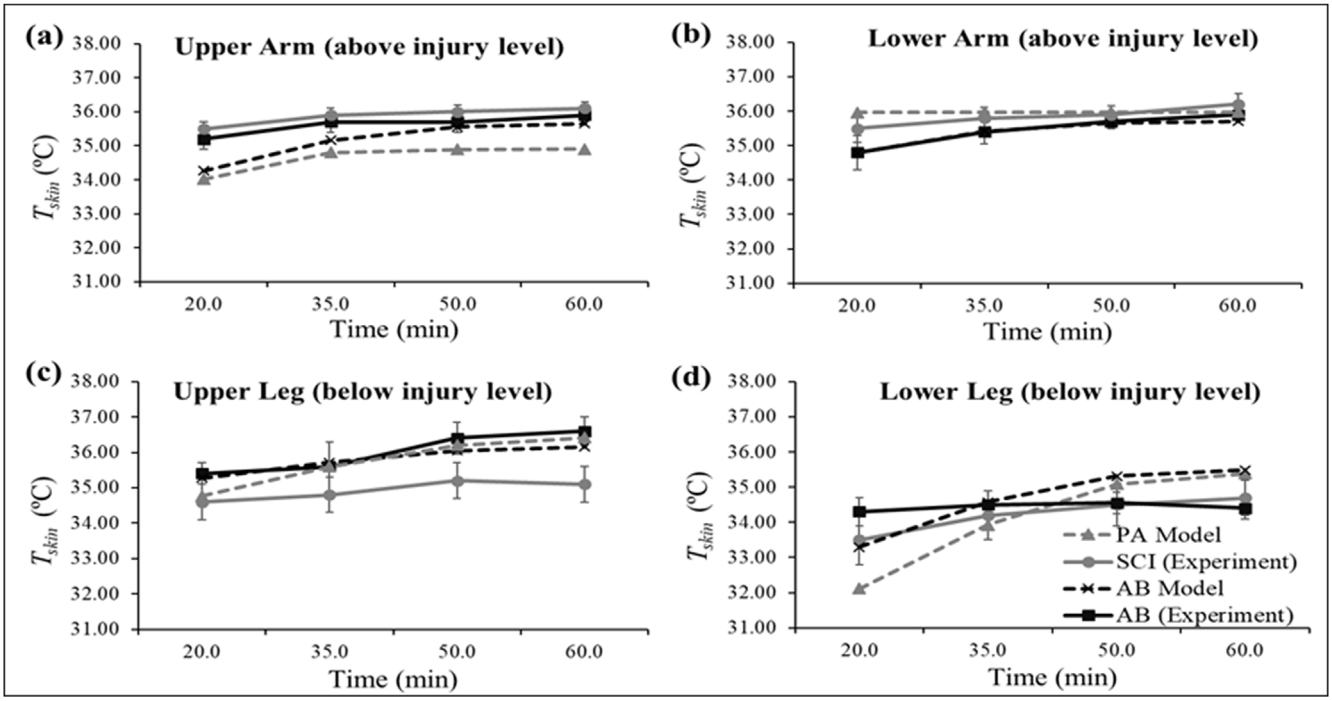

Fig. 5. Line plot of predicted and observed values of T_{skin} of (a) upper arm (b) lower arm (c) upper leg and (d) lower leg, for both groups PA and AB seated at rest at different room temperatures and relative humidity 45% (Attia and Engel, 1983).

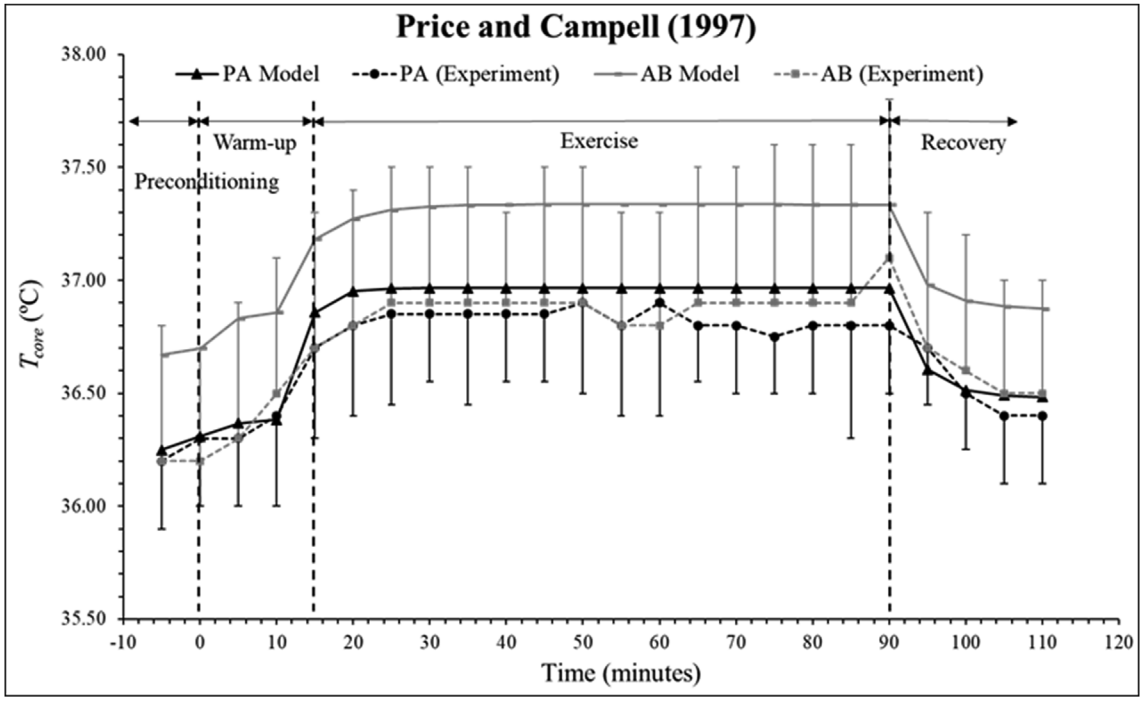

Fig. 6. Line plot of predicted and observed values of T_{core} for both groups PA and AB during rest, exercise and post recovery at room temperature 21.5 (1.7) ˚C and relative humidity 47.0 (7.8) % (Price and Campbell, 1997).

the obtained values were used to calculate SBP of the body about its threshold T_{core} in PA using Eqs. (3a)–(3c) (Mneimneh et al., 2018). This is applicable for all thoracic SCI levels (Cooper et al., 1957).

$$\dot{m}_{skin} = \frac{\dot{m}_{skin,dil} \cdot \dot{m}_{skin,con}}{\dot{m}_{skin,-basal}} \tag{3a}$$

$$\dot{m}_{skin,dil} = \begin{cases} \dot{m}_{skin-basal} for\ T_{cr} \le T_{cr_threshold}\,^{\circ}C \\ \frac{T_{cr} - T_{cr_threshold}}{38.2 - T_{cr_threshold}} (\dot{m}_{skin,max} - \dot{m}_{skin-basal}) \\ \quad + \dot{m}_{skin-basal} for\ T_{cr_threshold}\,^{\circ}C < T_{cr} < 37.3^{\circ}C \\ \dot{m}_{skin,max} for\ T_{cr} \ge 37.3^{\circ}C \end{cases} \tag{3b}$$

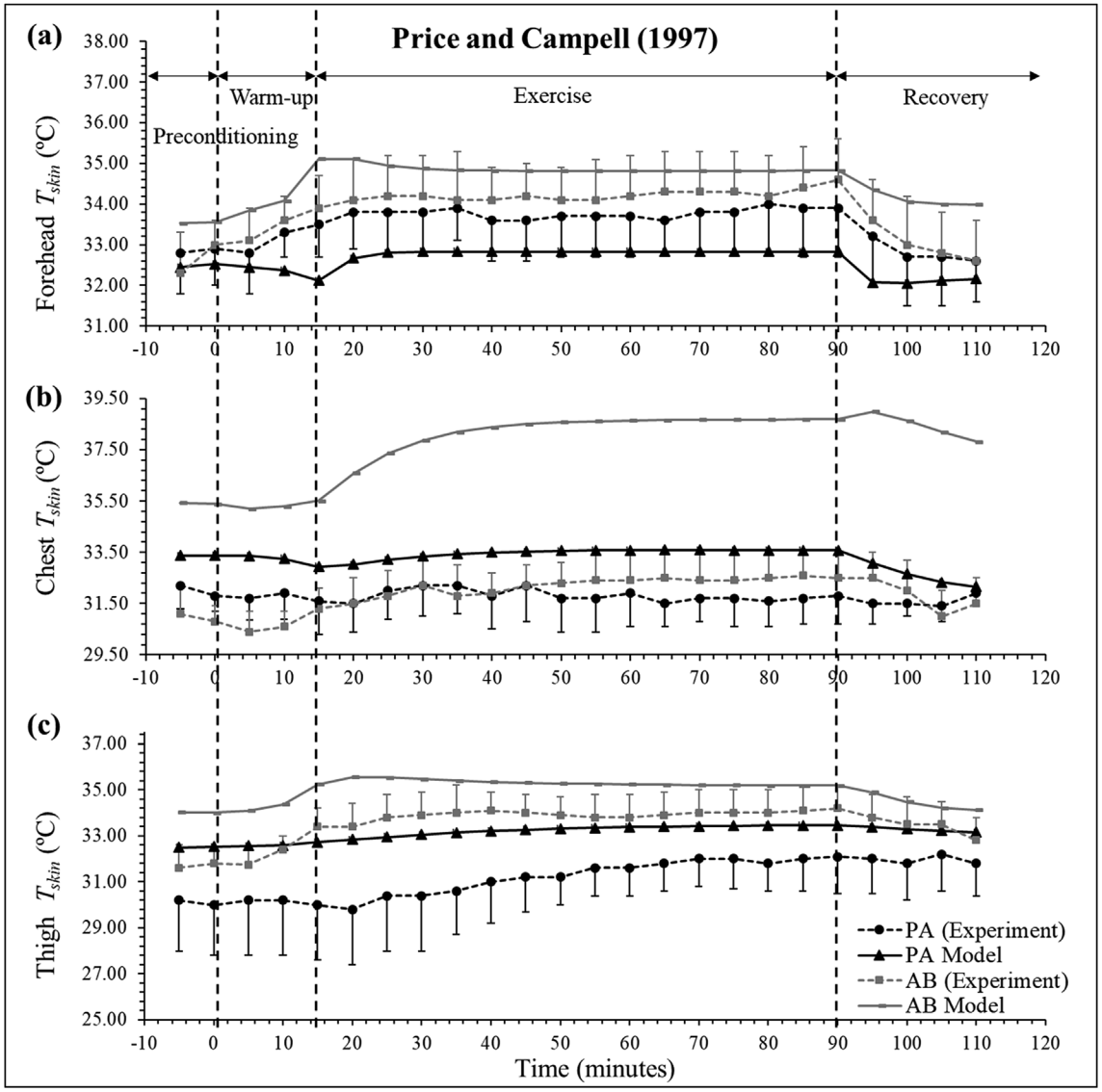

Fig. 7. Line plot of predicted and observed values of T_{skin} of (a) forehead (b) chest and (c) thigh for both groups PA and AB during exercise at room condition 21.5 (1.7) ˚C and 47.0 (7.8) % (Price and Campbell, 1997).

$$\dot{m}_{skin,con} = \begin{cases} \dot{m}_{skin,min} for\ T_{cr} \le 35.12°C \\ \frac{T_{cr} - 35.6}{T_{cr_threshold} - 35.6}(\dot{m}_{skin-basal} - \dot{m}_{skin,min}) \\ \quad + \dot{m}_{skin,min} for\ 35.12\ °C < T_{cr} < T_{cr_threshold}\,°C \\ \dot{m}_{skin-basal} for\ T_{cr} \ge T_{cr_threshold}\,°C \end{cases} \quad (3c)$$

Hot and cold control equations (sudomotor and shivering): after thoracic SCI, PA are prone to instability in T_{core} in hot and cold climates (or even exercise) due to the absence of sudomotor (sweating) and shivering for segments below injury level. This is implemented in the altered Bioheat model for PA by modifying the weighting factor of each SWEAT and COLD, representing the sudomotor and shivering responses respectively. Compared to AB, sweat rate is reduced by 10% from the whole body in PA, yet it is increased by 1.5 and 1.2 for the head and palms respectively as reported in literature (Fitzgerald et al., 1990; Wilsmore, 2007). For the segments below injury level (T6-T12), neither sweat nor shivering was observed (Petrofsky, 1992; Wilsmore, 2007). Thus, in the altered bioheat model, the weighting factor of SWEAT and COLD was modified to zero for the impaired body segments including thighs, calves, feet, lower back (defined by right and left lower back in the model) and abdomen (defined by right and left lower front in the model). The remaining body segments above injury level had SWEAT, and COLD weighting factors as summarized in Table 5.

3.2. Integration of PCM and ice cooling vests models in PA model

3.2.1. Fabric-PCM model and fabric-ice model

Based on published work on fabric-PCM cooling vest by Itani et al. (2016), the cooling vest was decomposed in to several layers interacting through heat and mass equations. As shown in Fig. 2, first, the outer fabric layer of the vest was exposed to the ambient; while the inner fabric layer was assumed to be near the torso skin layer. Between these two layers, there were two types of air layer: macroclimate and microclimate. The former occupied the free space between PCM packets and outer fabric layer; whereas, the latter occupied the free space between PCM packs and the inner layer. The PCM cooling vest contained PCM packets located at front and back of the vest to cover the chest and trunk segments.

Because PCM packet had the lowest temperature among the different layers, it absorbed heat by conduction, convection and radiation from the surrounding micro and macroclimate air layers of the vest. The microclimate air layer exchanged heat with the inner fabric and PCM. On the other hand, the macroclimate air layer exchanged heat with the

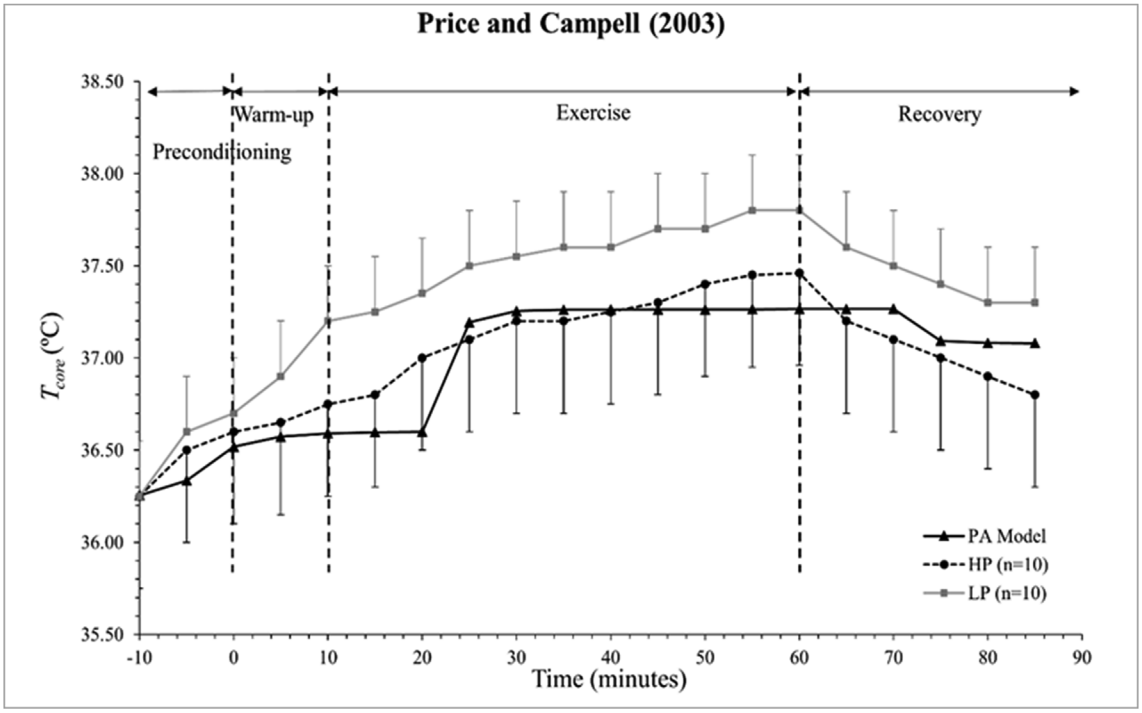

Fig. 8. Line plot of predicted values of T_{core} for PA compared to that of experimental values of people with high thoracic SCI (HP) and people with low thoracic SCI (LP) during exercise at room temperature 31.5 ± 1.7 °C and relative humidity 42.9 ± 8.0% (Price and Campbell, 2003).

PCM, inner fabric layer and outer fabric layer. The outer fabric layer exchanged heat with the surrounding environment. The PCM cooling vest may help in reducing skin temperature of PA and eventually reduce core temperature through increasing sensible heat losses for torso segments, especially un-paralyzed active ones. Since perspiration is disrupted in these segments (Wilsmore, 2007), it is less probable for the PCM cooling vest to encounter any problem with moisture accumulation because sweat glands at the trunk skin site are inactive and sweat production at the chest skin area is negligible compared to that of the head and palms (Wilsmore, 2007). All heat and mass equations of the PCM model are detailed in the study of Itani et al. (2016) and Hamdan et al. (2016). Model validation is achieved by comparing predicted results with the reported experimental results for PA in literature.

Modelling the effect of ice cooling vest on PA during exercise follows similar approach to that of the PCM cooling vest of 15 °C melting point. Yet, the physical properties of ice (melting point, latent heat of fusion per unit volume, specific heat, density and thermal conductivity) differ from those of PCM agent used. Due low melting temperature of ice, the ice packet located at the front and back of the vest may be effective in reducing skin temperature and consequently reducing core temperature. The ice vest model integrated with PA bioheat model is validated by comparison with available published data.

3.2.2. Boundary conditions for the cooling vest models

The integration of the bioheat model with the PCM and ice cooling vest models was done by ensuring continuity of heat at the skin surface to the inner fabric at any time. T_{core} and T_{skin} of the chest, back and abdomen were calculated from the fabric-PCM or fabric-ice subroutine integrated in PA-bioheat model, while T_{core} and T_{skin} of the remaining body segments were calculated by the energy equations that didn't include any PCM or ice effect within the fabric layers. Integrated models followed boundary conditions of the inner fabric – skin surface as those presented in Hamdan et al. (2016) and Itani et al. (2016) depending on human activity level. These conditions include moisture diffusion in vapour form into the fabric with no sweat accumulation, or moisture diffusion and limited sweat accumulation, or sweat accumulation captured by inner fabric. This was applied for the active segments above injury level; whereas, for impaired segments below injury level, only moisture diffusion in vapour form into the fabric with no sweat accumulation is expected due to absence of perspiration at insensate skin. *A* contact thermal resistance existed between the skin and inner fabric was considered due to the air layer filling the gap between the two surfaces. With a thickness of 1.3 mm, air layer's thermal dry resistance was calculated using Eq. (4) (Stephan and Laesecke, 1985):

$$\text{Dry resistance: } R_{d_airlayer} = \frac{th_a}{k} \quad (m2/W) \tag{4}$$

where k = 24 mm W/m^2·C, and th_a = air layer thickness (assumed 1.3 mm in the model).

3.2.3. Numerical solution

The heat and mass transfer energy equations for the PCM/Ice-PA bioheat model were solved numerically using the explicit Euler forward method, given the initial values of core and skin temperatures of the trunk and chest, pressure of all different layers of clothing and air, and initial PCM or ice temperature. Before running the bioheat model for PA, initial conditions for the remaining body segments including temperature and pressure of clothing layers were provided from saved database for PA at moderate sedentary conditions. At a specified time reading (t + Dt where Dt = 0.02 s taken in this model), the Fabric-PCM subroutine was called first to calculate the skin and core temperatures of segments whose clothing layers included PCM or ice packet (chest, abdomen, lower back and upper back). Before looping in to PA bioheat model, PCM or ice computed temperature was compared to its melting temperature to identify whether to update its temperature if it's higher than its melting temperature else to keep it the same and calculate melted fraction of PCM or ice packet. Then, using bioheat model for PA, skin and core temperatures were calculated for the remaining body parts excluding torso. After each complete iteration, the average values of core temperature and cardiac output were calculated and compared to threshold values of thermoregulatory responses in PA to identify whether vasomotor, sudomotor or shivering to be activated for body segments above injury level. These steps were looped over until the

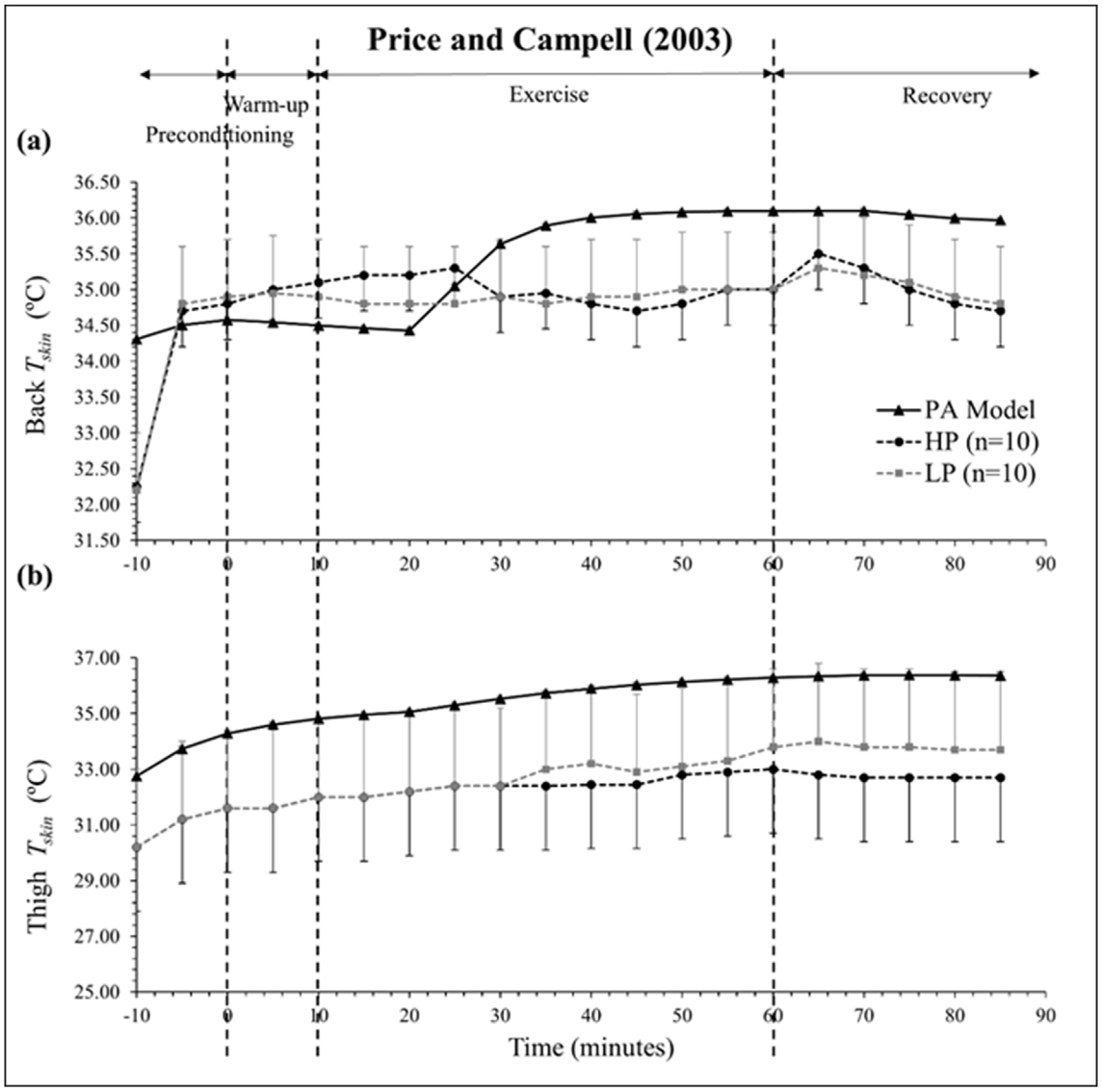

Fig. 9. Line plot of predicted values of T_{skin} of (a) back and (b) thigh for PA compared to that of people with high thoracic SCI (HP) and people with low thoracic SCI (LP) during exercise at room temperature 31.5 ± 1.7 °C and relative humidity 42.9 ± 8.0% (Price and Campbell, 2003).

simulation time duration was finished. The time step for the numerical methodology of integrated PCM or ice vest model with the PA model is presented in Fig. 3.

4. Validation of PA bioheat model and its integration with cooling vest for MET > 4

The altered Bioheat model for PA was validated with reported data in literature for Attia and Engel (1983), Price and Campbell (1997, 2003). Each experimental study was focused on specific climate and activity level (specific metabolic rate). Comparison of T_{core} and T_{skin} values was done between the predicted values by the altered model and the observed ones in the study. The model predictions showed an accuracy with a maximum deviation in core and local skin temperature values compared to the experimental studies: 0.46 °C and 1.48 °C compared to Attia and Engel (1983), experiment, 0.22 °C and 3 °C compared to Price and Campbell (1997), and 0.75 °C and 1.83 °C compared to Price and Campbell (2003). In addition, the segmental sensible and latent heat losses of the torso were obtained from the validated PA model to understand the effect of the impairment in thermal physiology on heat loss compared to that of AB. Then, the fabric-PCM-PA model was validated with Trbovich et al. (2014) and the fabric-ice-PA model was validated with Armstrong et al. (1995). The comparison was done between predicted and experimentally reported values of T_{core}. In addition, the predicted latent and sensible heat losses from the torso segments for *no-vest* and *with-vest* cases to assess the cooling effectiveness. The comprehensive details of each experiment and validation results are provided in this section.

4.1. Validation of PA Bioheat model

To validate the robustness of PA Bioheat model, three published experimental studies were selected. Table 6 presents the detailed criteria of the selected experimental studies of each of Attia and Engel (1983), and Price and Campbell (1997, 2003). It was noted that the difference in injury level was taken into consideration and presented in the form of standard deviation for the measured variables (core and skin temperatures). In addition, the clothing thermal characteristics were specified based on reported data in each work. Additional thermal fabric resistance was incorporated in the model for the back and thighs that are in contact with wheelchair support material of the seated PA participant. Each of the three protocols was implemented in the altered

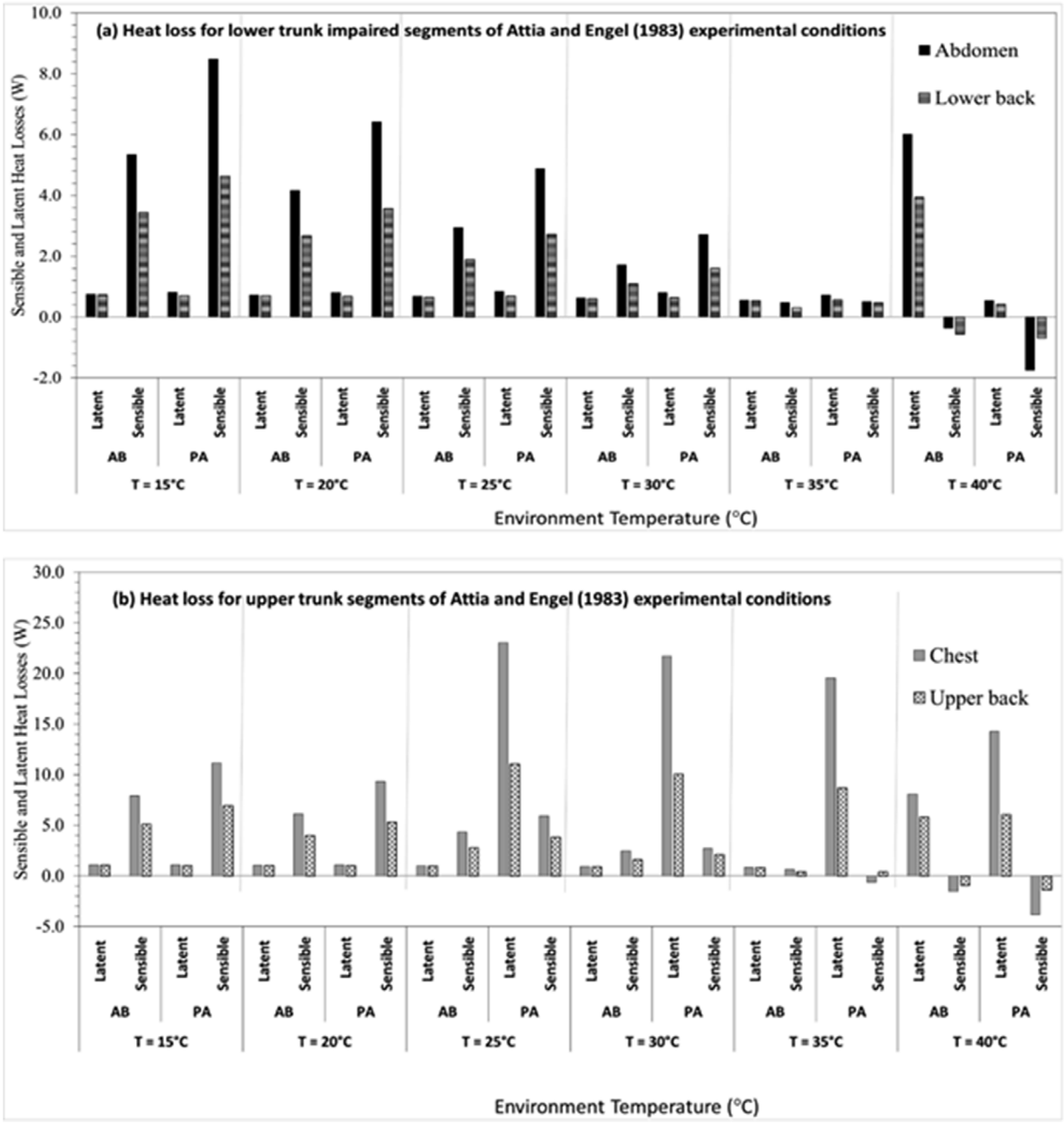

Fig. 10. Bar graph of sensible and latent heat losses in AB and PA at different room temperatures (15,20,25,30,35,40 ˚C) at the (a) inactive parts of torso (abdomen and lower back) and (b) active parts of torso (chest and upper back).

bioheat model for PA, and values of T_{core} and segmental T_{skin} were plotted for each climate/experiment. Moreover, the Salloum et al. model (2006) was used to predict the steady state of T_{core} and segmental T_{skin} for AB for the first two studies only. Results showed that the model predicts T_{core} and segmental T_{skin} within a limited accuracy in core and local skin temperature values compared to the experimental studies: 0.46 °C and 1.48 °C compared to Attia and Engel (1983), experiment, 0.22 °C and 3 °C compared to Price and Campbell (1997), and 0.75 °C and 1.83 °C compared to Price and Campbell (2003). However, the model limitation can be justified by the fact that PA persons have inherent diversity in their level of injury, its severity and duration, disruption in thermoregulation and physical fitness.

Fig. 4 shows the predicted and observed values of T_{core} of Attia and Engel (1983) experiment for both groups PA and AB. Predicted values by PA model show an average deviation of 0.279 ± 0.176 ˚C from experimental results, while the predicted values by AB model show an average deviation of 0.064 ± 0.052 ˚C. At low indoor temperatures (< 20 ˚C) and high indoor temperatures (> 35 ˚C), the PA model appears to under predict T_{core} values by 0.46 °C, while at moderate room temperatures (20–35 ˚C), the model seems to show less deviation from the experimental results (0.08 °C). Therefore, the PA model can predict T_{core} values within a maximum error of 0.46 °C at high and low ambient conditions.

Fig. 5(a–d) presents the transient change in segmental skin temperatures for upper arm, lower arm, upper leg and lower leg respectively, at room temperature 35 ˚C and relative humidity 45% when seated at rest of Attia and Engel (1983) experiment. The predicted values of T_{skin} for upper arm and lower arm and upper leg and lower leg followed similar trends as observed experimentally. Fig. 5a shows the increase in upper arm skin temperature of PA predicted by the model

Table 7
Experimental protocol of Armstrong et al. (1995) and Trbovich et al. (2014).

Experiment	Armstrong et al. (1995) Ice vest	Trbovich et al. (2014) PCM vest
Room temperature	32.9 ± 0.1 °C	21.1–23.9 °C
Relative Humidity	75%	50%
Exercise Type	Pushing custom-built chair on a stationary roller	Intermittent sprint of wheelchair
Duration of exercise	30 min	60 min
Clothing	Shorts and socks without shirts	Shorts and socks without shirts
Cooling methodology	Ice vest	PCM vest
Melting Temperature	0 °C	15 °C
vest weight	3 kg	2.27 kg
coverage skin area	0.14 m^2	0.061 m^2
Number of packs	12 ice packs	4 PCM packs
Vest used		
Vest Supplier	Steelevest; www.steelevest.com	Glacier Tek, Inc., West Melbourne, FL

with deviation mean of 1.307 °C and standard deviation of 0.137 °C from the experimental values. Fig. 5b shows the increase in lower arm skin temperature of PA predicted by the model with deviation mean of 0.216 °C and standard deviation of 0.168 °C. Because vasodilation is still active for the lower arm (forearms) in PA, its skin temperature showed transient change similar to that of experimental results of AB. Yet, the higher absolute values of T_{skin} of the lower arm is due to the increased SBP after SCI injury. Fig. 5c shows the increase in upper leg skin temperature of PA predicted by the model with deviation mean of 0.972 °C and standard deviation of 0.452 °C. It remained lower than that of AB due to absence of vasodilation for upper leg which is a body segment below injury level. Finally, Fig. 5d shows the increase in lower leg skin temperature of PA predicted by the model with deviation mean of 0.632 °C and standard deviation of 0.434 °C. It showed lower values than that of AB due to lack of vasodilation in that body segment as seen in upper leg skin temperature of Fig. 5c.

Fig. 6 presents the transient change in the simulated results and observed measurements of T_{core} of PA and AB in the study of Price and Campbell (1997) (Table 6), T_{core} showed a slight increase prior to exercise during preconditioning phase of the experiment when participants were at rest. Then, an increase in T_{core} values was obtained until a steady state was reached till the end of exercise (time = 90 min) when heat gain and heat dissipation of the body were balanced. Finally, a drop in T_{core} values was observed in the passive recovery post exercise (time > 90 min). The predicted values for PA showed similar trend to that of the observed experimental results but with an average deviation of 0.11 (0.056) °C from them. Whereas, predicted values by AB model were higher than that of experimental values with an average deviation of 0.426 (0.075) °C. Although the predicted values by PA and AB models showed difference not seen in the experimental results, predicted T_{core} values were still within the standard deviation of those of the experiment. Moreover, the obtained difference for PA model prediction is justified by the difference in injury level between participants and their physical characteristics whether trained and trained. In general, PA model seems to over predict T_{core} values but with an acceptable accuracy at moderate ambient conditions (21.5 ± 1.7 °C and 47.0 ± 7.8%) as seen in the case study of Attia and Engel (1983) at moderate indoor conditions (20–35 °C and 45%).

In Fig. 7(a–c), the transient change in segmental skin temperatures for forehead, chest and thigh were plotted for both AB and PA and compared to the experimental ones. Fig. 7a showed an increase in the predicted values of forehead skin temperature during exercise at a deviation mean 0.855 (0.278) °C for PA and at a deviation mean 0.749 (0.15) °C for AB, both compared to that of experimental results (Price and Campbell, 1997). Fig. 7b showed an increase in the predicted values of chest skin temperature during exercise at a deviation mean 1.5 (0.413) °C for PA compared to that of experimental results. Fig. 7c displayed an increase in the predicted values of thigh skin temperature during exercise at a deviation mean 1.96 (0.55) °C for PA and at a deviation mean 1.48 (0.46) °C for AB, both compared to that of experimental results. It was observed that T_{skin} values of the active body parts in PA (head and chest) were similar that of AB because sweating was active for sensate skin in PA (Price and Campbell, 1997). Whereas, T_{skin} values of the impaired body parts in PA (thigh) was lower than that of AB due to reduced SBP responsible for heat dissipation from the core to the skin and surrounding (Muraki et al., 1995). Therefore, any increase in T_{skin} values for body segment below injury level would be the result of: (i) progressive heat storage in the core that is transferred by conduction to the skin, (ii) the effect of convection and radiation heat transfer at the skin with the environment and finally, (iii) lack of perspiration for these segments.

Fig. 8 shows the simulated results of T_{core} of PA for the study of Price and Campbell (2003) where a slight increase was observed during warm-up phase of the exercise (time < 20 min). Then, T_{core} started to rise till the end of exercise (time = 60 min). Finally, a drop in T_{core} values was observed in the post recovery (time > 60 min). The predicted values for PA showed similar trend to that of the observed experimental results for people with high thoracic SCI (HP) with a mean of difference of 0.236 (0.146) °C, and for people with low thoracic SCI (LP) with a mean of difference of 0.57 (0.216) °C. The gradual increase in T_{core} values for PA during exercise indicated that heat gain in the body was higher than heat dissipation due to the disrupted thermoregulatory responses for impaired segments in PA (absence of vasodilation and sweating).

Fig. 9a shows an increase in the predicted values of back skin temperature during exercise at a deviation mean 0.978 (0.688) °C compared to HP and at a deviation mean 1.016 (0.572) °C compared to LP. Fig. 9b showed an increase in the predicted values of thigh skin temperature during exercise at a deviation mean 2.955 (0.225) °C compared to HP and at a deviation mean 2.493 (0.312) °C compared to LP. At time ≥ 20 min, back skin temperature predicted by the PA model showed 1.3 °C rise within 20 min and remained steady till the end of the exercise. This transient change in skin temperature was due to the increase of metabolic rate of PA defined in the model with respect to the protocol of the exercise reported in the study. In the experiment, the subjects were initially preconditioned at lab room temperature at rest within 10 min prior to exercise. Then, they performed certain warm-up for 10 min until they started exercising at gradual increase in the exercise intensity to a specific power till the end. Consequently, as metabolic rate increased, heat generation in PA increased and was transferred to the skin. Thus, back's skin temperature of PA increased. For both predicted and experimental results, as sweating did not occur in areas of insensate skin for the back and thigh, their T_{skin} values increased during exercise because heat was not dissipated from the body through evaporation at the impaired segment below injury level.

The continual increase in T_{core} values and segmental T_{skin} values for impaired body parts of PA during exercise indicated the inability of PA to regulate their body temperature. Although they maintained vasomotor response and sweating for body segments above injury level, they were still susceptible to thermal stress at high ambient conditions (see Fig. 4) because of the disruption in thermoregulatory responses for

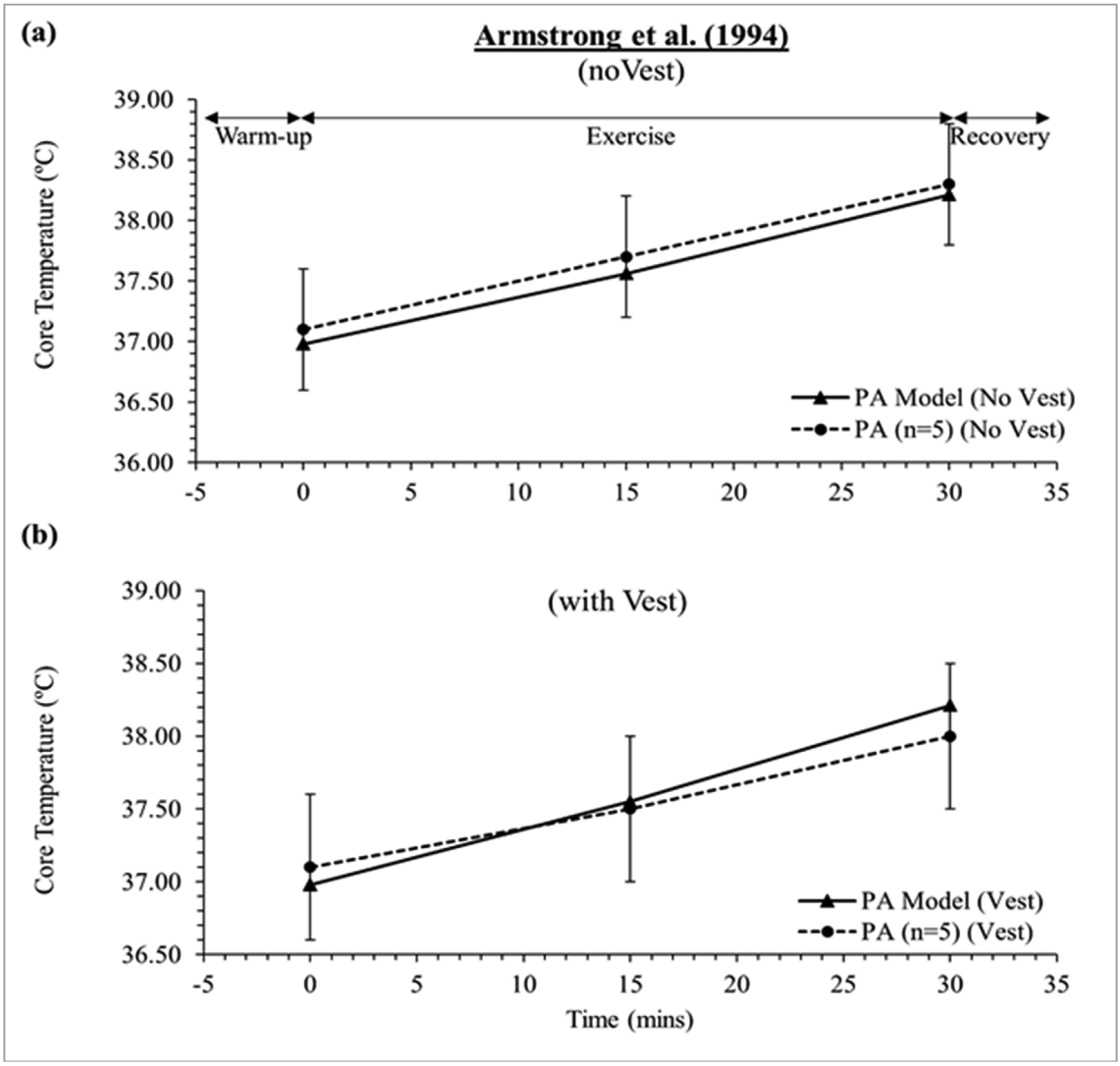

Fig. 11. Line plot of predicted values of T_{core} for PA with and without PCM cooling vests compared to that of experimental values during exercise at room temperature 32.9 ± 0.1 °C and relative humidity 75% (Armstrong et al., 1995).

Table 8
Steady state of latent and sensible heat losses of torso in PA for *no-vest* and *with-vest* cases of study in Armstrong et al. (1995) experiment.

Torso segment	*no-vest heat loss*		*with-vest heat loss*	
	Latent	Sensible	Latent	Sensible
	(W)	(W)	(W)	(W)
Abdomen	0.52	2.10	0.33	6.56
Lower back	0.44	1.19	0.36	6.81
Chest	14.65	2.51	0.24	8.40
Upper back	6.21	1.33	0.45	8.49

the impaired body segments below injury level. To understand the changes in thermal response of PA compared to that of AB, segmental sensible and latent heat losses were calculated using the PA bioheat model and AB bioheat model for the case study of Attia and Engel (1983).

Fig. 10 shows the predicted heat losses of the chest and upper back and the abdomen and lower back parts of the torso at different ambient temperatures for both AB and PA. Starting with torso segments below injury level, at room temperature below 25 °C, the latent heat loss of abdomen and lower back was similar between PA and AB, yet sensible heat loss was higher for PA than AB due to lack of vasoconstriction at the impaired torso segments (see Fig. 10a). Thus, heat dissipation at the insensate skin increased and eventually T_{core} value for PA was lower than that of AB (see Fig. 4). While at room temperature above 35 °C, latent heat dissipation in AB increased rapidly because of perspiration at the abdomen and lower back, yet no increase was noticed for that of PA due to absence of sweating. The PA sensible heat gain at room temperature of 40 °C showed an increase in body heat resulting in higher value of T_{core} for PA compared to that of AB (see Fig. 4). The heat gain experienced by PA was due to higher environmental temperature compared to T_{skin} values of PA.

For the torso segments above injury level, Fig. 10b shows that at room temperature below 25 °C, chest and upper back witnessed higher sensible heat losses than latent ones for both PA and AB, yet the losses were similar between the two groups due to conservation of vasoconstriction and SBP rates for the active parts of torso above injury level as explained in previous section. However, at room temperature above 25 °C, latent heat losses of PA were much higher than that of AB indicating higher rates of sweating at sensate skin of chest because T_{core} value of PA reached its sweating threshold (see Table 3). The high sweating rate in PA was justified as an altered thermoregulatory response of the body to reduce T_{core} value and reduce heat storage. Also, at hot ambient condition (30 °C and above), latent heat losses were less

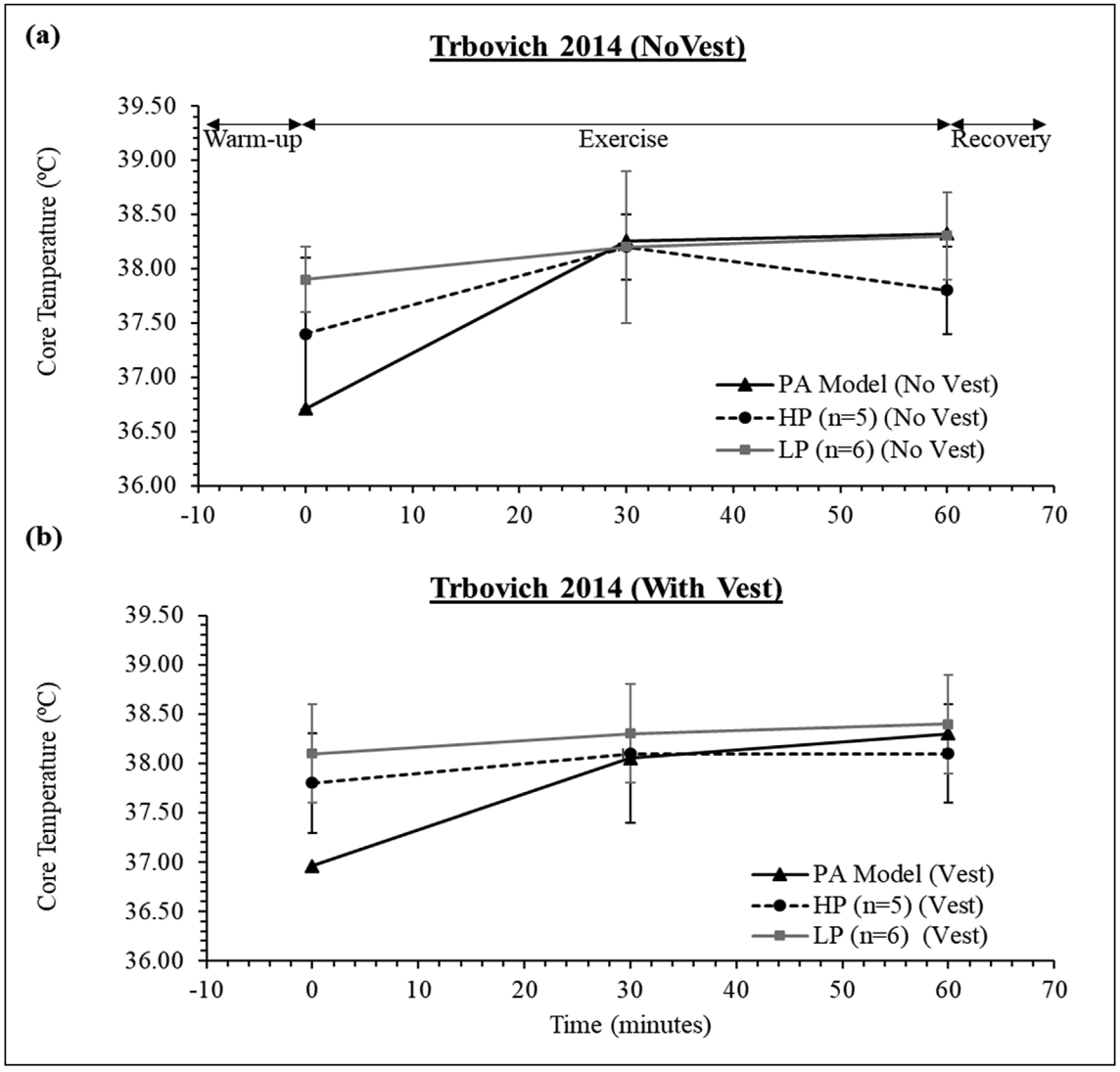

Fig. 12. Line plot of predicted values of T_{core} for PA with and without PCM cooling vests compared to that of experimental values during exercise at room temperature (21.1–23.9 ˚C) and relative humidity 50% (Trbovich et al., 2014).

Table 9
Steady state of latent and sensible heat losses of torso in PA for *no-vest* and *with-vest* cases of study in Trbovich et al. (2014) experiment.

Torso segment	*no-vest heat loss*		*with-vest heat loss*	
	Latent	Sensible	Latent	Sensible
	(W)	(W)	(W)	(W)
Abdomen	1.05	4.40	0.08	6.22
Lower back	0.81	2.67	0.15	5.72
Chest	21.71	5.75	0.14	9.66
Upper back	13.62	3.10	0.26	8.61

Table 10
Stored heat values calculated for *no-vest* and *with-vest* cases in the studies of Armstrong et al. (1995) and Trbovich et al. (2014).

PA Case	Rate of body heat storage (H_{stored})	
	Ice vest (Armstrong et al., 1995	PCM vest Trbovich et al. (2014)
no-vest	165 W	124 W
with-vest	161 W	109 W

than the case of moderate ambient condition (below 30 ˚C) because skin vapor pressure approached ambient vapor pressure of saturation at the torso segments above injury level. Thus, T_{core} value was observed to be higher in PA compared to that of AB (see Fig. 4).

In summary, PA bioheat model predicted accurately PA thermal response compared to the experimental results of Attia and Engel (1983) and Price and Campbell (1997, 2003). Furthermore, the calculated latent and sensible heat losses at the active body segments were higher than those of inactive as presented by PA model for the case study of Attia and Engel (1983). Therefore, for the purpose of enhancing the effectiveness of cooling in PA at hot climatic condition and intense activity such as arm-crank exercise, cooling should target the skin site of torso where sensible heat losses may be incremented to reduce T_{core} values in PA and avoid thermal stress.

4.2. Validation of PA Bioheat model with cooling PCM cooling vest and ice cooling vest

Simulations were done based on published experimental work for Trbovich et al. (2014) and Armstrong et al. (1995). Each experimental study was focused on specific type of cooling vest at moderate and high climate condition and activity level (specific metabolic rate). Table 7 presents the protocol of the two experiments; Armstrong et al. (1995)

and Trbovich et al. (2014). The duration of the exercise in Trbovich et al. (2014) was twice that of Armstrong et al. (1995), yet the indoor room conditions were higher in the latter. Both experiments aimed at studying the effectiveness of each vest on reducing T_{core} of PA; thus, each exercise was repeated twice, with and without the cooling vest. In both experiments, participants wore shorts and socks without shirts during *with-vest* case; while, the sleeveless vest covered the abdomen, back and chest, yet the PCM packets or ice packs were mainly located at the abdomen and lower back area of the participant who was at seating position performing certain activity level.

Fig. 11(a–b) shows the predicted values of T_{core} for *no-vest* and *with-vest* simulations compared to that of the experiment of Armstrong et al. (1995) study where the participants were wearing ice cooling vests. An average deviation from the experimental results was obtained at 0.116 °C and standard deviation of 0.026 °C for the *no-vest* case, and at 0.167 °C and standard deviation of 0.153 °C for the *with-vest* case. Although the experimental values of T_{core} were increasing in both cases, the maximum value reached *with-vest* was slightly less than that obtained in *no-vest* (no vest: $T_{core} = 38.3 \pm 0.1$ °C, with vest: $T_{core} = 38.0 \pm 0.1$ °C). Yet, the predicted values of T_{core} by the fabric-ice-PA model showed negligible difference between the two cases indicating that using ice cooling vest didn't affect T_{core} value of PA during exercise. This outcome was obtained in the experimental study of Armstrong et al. (1995).

To understand the effect of ice vest on thermal response of PA during exercise, latent and sensible heat losses of the torso were calculated using Eq. 5(a, b):

$$Q_{latent} = A_{skin} \times \frac{P_{skin} - P_{if}}{R_{e_air\ layer} + R_{inner\ fabric}} (W) \quad (5a)$$

$$Q_{sensible} = A_{skin} \times \frac{T_{skin} - T_{if}}{R_{d_air\ layer} + R_{inner\ fabric}} (W) \quad (5b)$$

where A_{skin} is skin area in m^2, P_{skin} is skin pressure in kPa, P_{if} is the inner fabric pressure, T_{skin} is skin temperature (°C), T_{if} is inner fabric temperature (°C), $R_{d_airlayer} = \frac{th_a}{k} (m^2.°C/W)$, $R_{e_airlayer} = a\left(1 - e^{-th_a/b}\right)$ (m^2·kPa/W), $k = 24$ mm.W/m^2·C, th_a = air layer thickness (assumed 1.3 mm), a = 0.034 m^2 kPa/W and b = 15 mm (Stephan and Laesecke, 1985).

Table 8 summarizes the calculated heat losses of inactive torso segments (abdomen and lower back) and active torso segments (chest and upper back) of PA for both cases of *no-vest* and *with-vest* at the steady state attained at the end of the exercise.

In the no-vest case, sensible heat losses obtained were higher at the front side of torso that had less resistance with the ambient. Also, latent heat losses were minimal for abdomen and lower back as they are below injury level compared to the chest and upper back. After wearing the ice vest during exercise, sensible heat losses increased at the four skin sites of the torso; while, the latent heat losses decreased. The difference in effect of ice vest at different skin sites of the torso is justified by the different fabric resistances between the torso and the ambient condition that was set at 32.9 ± 0.1 °C. However, it can be concluded that wearing ice vest during exercise can contribute in increasing total skin sensible heat losses at the torso for PA. This increment may be insignificant for reducing T_{core} because when considering the coverage skin area by the ice vest, lower back and abdomen (trunk area) were mostly covered by the ice packets compared to the chest and upper back (Armstrong et al., 1995). In the absence of vasodilatation at the lower trunk area, less heat will be transferred from the skin layer to the inner core layer because skin blood perfusion is disrupted at the trunk skin site (trunk is an impaired body segment below injury level). Heat transfer between the core and skin layers was enhanced by conduction only in the vest case. Therefore, locating ice packets mainly at the lower trunk affected the performance of this cooling method on reducing T_{core} of PA during exercise.

Fig. 12 (a–b) shows the predicted values of T_{core} for PA in cases of *no-vest* and *with-vest* compared to that of the experiment of Trbovich et al. (2014) where LP and HP participants were wearing PCM vest. For the *no-vest* case, an average deviation of 0.422 ± 0.329 °C were obtained in comparison to HP, and an average deviation of 0.422 ± 0.666 °C in comparison to LP. For the *with-vest* case, a mean difference of 0.363 °C and standard deviation of 0.42 °C were obtained in comparison to HP, and a mean difference of 0.497 °C and standard deviation of 0.562 °C in comparison to LP. Independent of injury level (T1-T12), T_{core} was increasing in both cases of exercising, yet the rate of increase of T_{core} was attenuated during early stage of exercise when using vest as presented experimentally and by simulations.

As summarized in Table 9, sensible heat losses of back side of torso were lower than that of front side of torso due to extra insulation by chair; whereas, latent heat losses were higher for upper part of torso compared to lower one due to reduced effect of sweating for torso segments below injury level (abdomen and lower back). Comparing *no-vest* and *with-vest*, sensible heat losses at the four torso segments (abdomen, lower back, chest and upper back) showed an increase for the case of the *with-vest* case; while latent heat losses decreased. Therefore, wearing a PCM-vest during exercise can help increase total skin sensible heat loses for PA. However, the obtained results of PCM vest performance on cooling PA were not satisfactory because there was no change in T_{core} values after wearing the vest during exercise. The coverage skin area of the PCM packets wasn't enough to target upper body skin sites, mainly the upper back. Instead, the packets were located at the abdomen and lower back which are insensate and below injury level. Therefore, the cooling capacity of PCM vest was insufficient to remove stored heat from the core through skin to the surrounding because vasodilation disruption at these body segments decremented convective heat transfer through blood circulation (Cooper et al., 1957)."

To assess further the effect of each of ice and PCM cooling vests on thermal response in PA, the change in body heat storage was calculated at the end of each exercise in both studies: Armstrong et al. (1995) and Trbovich et al. (2014). Using the formula of Chou et al. (2008) defined in Eq. (6) and based on the initial and final average values of T_{core} and T_{skin} obtained by fabric-PCM-PA model and fabric-ice-PA model, the rate of change in body heat storage was obtained as shown in Table 10.

$$H_{stored} = (m_{body} \times C_P \times \Delta T)/t \ (Watt) \quad (6)$$

where m_{body} is the body mass applied in the altered bioheat model for PA in kg (72.335 kg); C_P is the specific heat of the body (3490 J/kg. °C), and ΔT is the change in body temperature, calculated by: $\Delta T = 0.8 \times \Delta T_{core} + 0.2 \times \Delta T_{skin}$ (Hardy et al., 1938), and t is the duration of exercise.

The heat stored in the body was reduced by 2.4% during a 30-min pushing wheelchair exercise in hot and humid room conditions in the study of Armstrong et al. (1995). Also, it was decremented by 12% during a 60-min intermittent-sprint exercise in moderate room condition in the study of Trbovich et al. (2014). However, this attenuation was insufficient for both studies which could be justified by the limited skin coverage area cooled by the packets which was below the critical body surface cooling area (~40%) (Kume et al., 2009).

To sum up, although wearing a cooling vest can help increase sensible heat losses at the torso skin site in PA, the effect of cooling was minimal on T_{core} values and stored heat in the body of PA during exercise. Based on obtained observations of Tables 8 and 9, locating the ice or PCM packets at torso can increase sensible heat losses, yet decrease latent losses. The location of ice or PCM packs can enhance overall performance of the vest for the sake of regulating thermal response in PA. However, other than pack location, the melting temperature should be taken into consideration when designing the cooling vest. Usage of ice may induce local cutaneous vasoconstriction that may prevent heat dissipation through convective cooling and predispose insensate skin to breakdown (House et al., 2012). Therefore, using PCM agents of melting points greater than 0 °C is recommended to avoid

individual's skin damage and occurrence of local vasoconstriction that restricts blood flow to the skin and turns it paler (Trbovich et al., 2014). Similar approaches were tested on athletic AB to find the optimum melting temperatures of PCM to attain acceptable comfort and sensation levels for the individual without causing any skin breakdown (Itani et al., 2018). A minimum of 10 °C melting point was shown to be effective in very hot ambient conditions for AB (Gao et al., 2012; Ouahrani et al., 2017). Therefore, further investigation on the selection of optimal melting temperature should be done for enhancing cooling effectiveness during exercise for PA.

5. Conclusion

The difficulty in PA subjects' recruitment limits the number of published experimental studies, and when thinking about the health safety issues for PA especially during exercise, it was worthwhile to develop a robust tool defined as a bioheat model for PA to predict their thermal response. Extending the bioheat model for TP developed by Mneimneh at al. (2018), necessary modifications were done based on the changes in the thermal physiology of the body after thoracic SCI. Then, the obtained model was combined with two cooling methods (ice and PCM vests) that were studied experimentally and published. Validation of PA bioheat model with and without each of the two cooling techniques was achieved showing good agreement between the predicted values T_{core} and the observed ones.

In general, this paper aimed at enhancing effectiveness of cooling techniques that may help PA in reducing heat gain and consequently reduce undesirable increase in T_{core} during exercise. Therefore, an altered bioheat model for PA integrated with cooling vest model was developed. By this model, it was possible to overcome experimental limitations that may be an obstacle in choosing the appropriate cooling method for PA for specific exercise and climate criteria. Therefore, predicted results of core and skin temperatures as well as sensible and latent heat losses in PA may serve as a database for addressing the effectiveness of cooling on PA. Future work may focus on combining other cooling methods such as evaporative cooling vest with PA bioheat model, to be validated with experimental work as well. Also, design criteria of an effective cooling vest for PA can be investigated by assessing the needed skin coverage area, PCM melting point and location of packets. Then, a comparative study may be conducted between different types of cooling vests to address their effect on thermal response of PA at certain level of exercise and environmental condition.

Acknowledgement

This publication was made possible by the Collaborative Research Stimulus grant award 24477-103557 of the American University of Beirut. The findings achieved herein are solely the responsibility of the authors.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jtherbio.2019.04.004.

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